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**System Design and Communication
Subsystem of an
Intelligent Projectile**

by
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fulfillment of the requirements for the degree of

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at the

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June 1997

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Abstract

The aerospace industry began as a market in which manufacturers for the most part had a known paying customer for their product. Even today, Boeing has aircraft buyers waiting in line for new 737 and 777 models. The industry has not fully developed, and the need of improved technology is still very present. However, as the industry matures this luxury is quickly eroding. Like most other industries, aerospace manufacturers in the future will have to independently determine some need that is present and they could fulfill, develop a product to meet that need, and then market their finished product. This can be a daunting process when considered in light of the million and billion dollar cost of most research and development programs in the aerospace industry.

Determining future national aerospace needs is a long and difficult process. Working as a project team, the MIT/Draper Technology Development Project had a challenging opportunity to project a future national aerospace need which could be best met by a group from MIT and Draper. This thesis documents the developmental process of an intelligent projectile from need determination through the preliminary design phase.

After a deliberate and thorough search, the team settled on a innovative aeronautical vehicle which could withstand a high-g launch then retrieve and transmit data to a remote ground station. Based on this fundamental premise, the team then began the design process to develop a system which would meet the desired objectives.

As the project developed, it became necessary to separate the projectile into subsystems in order to provide in depth analysis on different schemes that could meet the design objectives. The author specifically contributed to the design of the communications subsystem, so this thesis will concentrate heavily on that subsystem, though others will also be discussed.

The project is a two year project while this thesis only covers the first year of development. The status of the design, as well as the prospects for the future are discussed in detail.

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From a technical standpoint, the work on the communications subsystem would not have been possible if not for the tireless teaching of Joe Przyjemski. The hours he spent teaching me link budgets, autocorrelation functions, and power spectral densities will never be forgotten.

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1. Introduction

Chapter 1 will introduce the project and provide the impetus for the design. Also, Chapter 1 details the initial background research that was accomplished for the purpose of laying a foundation in which the best design decisions could be made.

Chapter 2 discusses the process used to determine opportunity areas for the design to progress and contribute. Also discussed are the lessons learned during this project and the recommendations for future programs endeavoring to accomplish the same task. This chapter finishes by focusing on a single system chosen to design and manufacture.

Chapter 3 relates the method used to determine the requirements of the system and traces the solidification of the system's functionality. The chapter includes a Quality Function Deployment (QFD) analysis and a Functional Flow Diagram (FFD) as part of the system preparation.

The first three chapters lead to the work discussed in Chapter 4, where three variants of the system were analyzed for feasibility. This chapter also details the final configuration of the vehicle and some of the introductory detailed design.

The next chapter details the decisions made on the communication subsystem. Characteristics of the mission which drove the subsystem are discussed. Several possible subsystem scenarios are analyzed in a link budget, and an enabling and innovative component design is introduced and analyzed.

Chapter 6 explains the role of the ground system in the project. This chapter also discusses the Tactical Control System (TCS) and the importance of TCS to the system.

The final chapter discusses the conclusions and recommendations that have come out of this research. The author points out both positive and negative aspects of the design and the process that was developed to produce that design.

1.1 MIT/Draper Technology Development Project--Draper Charge

The MIT/Draper Technology Development Project is a joint project executed by the students and faculty of the MIT Department of Aeronautics and Astronautics (Aero/Astro) and funded and supported by the Charles Stark Draper Laboratory (Draper). The project was initiated to enhance the working relationship between Draper and the MIT Aero/Astro Department while at the same time providing an educational exercise that could stimulate

creativity and entrepreneurship in engineering students. Table 1 shows the most important objectives proposed by Draper. The mission of the project is to decide the most effective way the assembled team could address one of the United States' pressing national aerospace needs within two years.

Table 1: Elements of the Draper Charge

• Concept to HW/SW in 2 yrs	• First-of-a-kind	• High Risk, "Unobtainium"
• Nationally important	• Strong customer focus	• Take full advantage of Draper and MIT capabilities
• Market survey and competitive analysis	• Emphasize creativity and innovation	• Multi-disciplined, system-based concept development

With the desires of the funding agency in mind, then, the output of the project can be classified into separate product and process results. The product of the project is to be a prototype or demonstrator of the technology that addresses a designated national aerospace need. This prototype must be developed in less than two years and must be manufacturable at either MIT or Draper.

Though this physical component is meaningful, the study of the process of need determination and fulfillment is also important. Since the aerospace defense market continues to shrink, this process will be important to the aerospace companies which would like to compete in the future.

1.2 Project Plan

The project plan to accomplish Draper's goals can be seen in Figure 1.¹ This Milestone Schedule provides a good overview of the project origins and future.

The project began with the proposal to Draper in May 1996 and was funded in July 1996. A database of information was compiled in July and August 1996 which would lay a foundation for the opportunity identification. This opportunity identification would take all of September 1996 and lead to a group of several ideas. These ideas would in turn be pared to a manageable list of concepts by the end of following month.

By the close of November, the team performed a market assessment for the remaining ideas. These market appraisals led to the selection of a final concept by the Christmas break. After receiving Draper's approval on the choice, the team began its system design for the product. This began with a planning phase for the project in which risk, possible problem areas, and other contingencies were identified and planned for. The planning phase was completed by January 1997, which paved the way for system development throughout the rest of the semester ending in May 1997.

Each of these phases is explained in more detail throughout the report, but this overview should give the reader a good idea of how this paper will develop and the direction of the project flow.

¹ Graphic in Figure 1 was developed by Charles Boppe. The Milestone Schedule was developed by Prof Boppe and Prof John Deyst.

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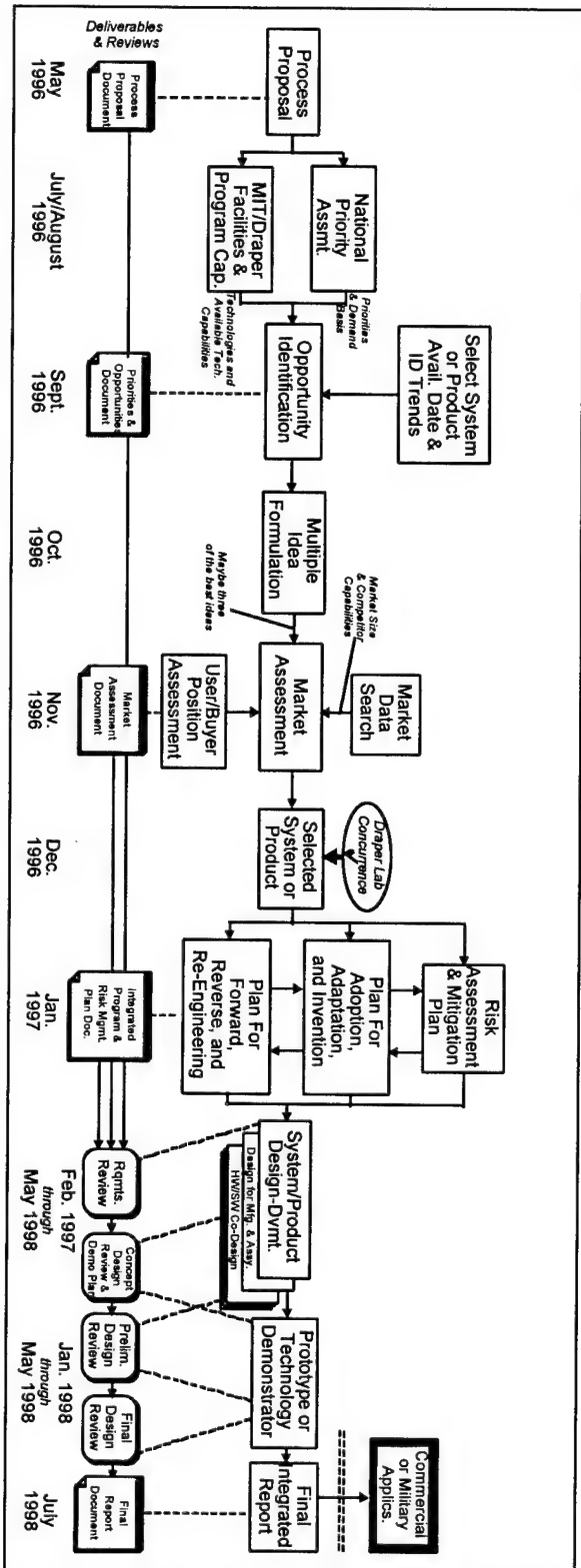


Figure 1: Milestone Schedule

2. Opportunity Generating Process

The process of anticipating a national aerospace need is quite complex. On one hand, the team did not want to inhibit creativity of thought. On the other hand, the final product of the process needed to withstand a certain level of scrutiny and engineering common sense. In order to best balance these objectives, the team put together the process flow shown in Figure 2.

2.1 Background Work

It is important to lay a firm foundation for any research project with such an open-ended product. The foundation for this project included an extensive literature search and an evaluation of the capabilities of the different sources of help for this project.

2.1.1 Literature Search

The literature search² acquired sources from the White House, the US Air Force, the US Navy, NASA, the FAA, and the EPA. Most of the research focused on recent documents and current industry leaders. The search produced a small library of information on the future of the aerospace industry in the US.

Many individuals were also personally contacted for professional opinions. These interviews were too varied in both value and content to list in entirety, but it should be noted that these professional opinions were factored into the teams brainstorming and development decisions.

² This literature research was performed mainly by team member Bernard Asare, a UROP student, before the rest of the team was assembled.

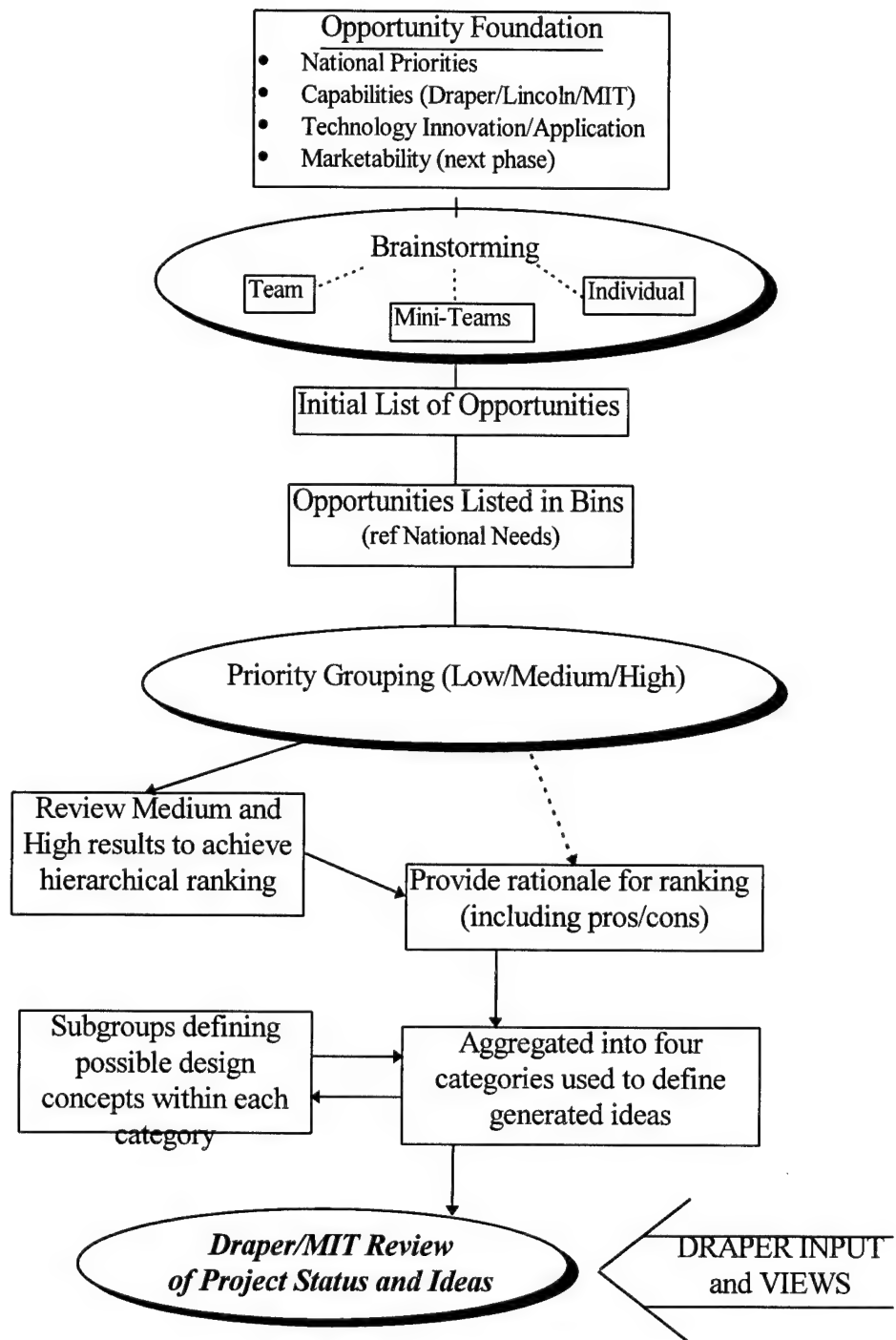


Figure 2: Opportunity Generating Process³

³ This figure created by team member Cory RA Hallam.

One of the most important documents discovered during this search was the National Critical Technologies List, produced by the White House in March 1995⁴. Using the ideals of US National Security and Economic Prosperity as goals, this document gave a direction for the future of the US technical thrust—or at least the governmental financial sponsorship of that thrust. In Table 2, the Critical Needs determined in this paper are separated into seven compartmentalized bins which describe general areas of research. These bins would later serve as a basis for capability assessments.

Table 2: White House Critical Needs Bins

	<i>Bin Name</i>	<i>Characteristic Technologies</i>
	Energy Efficiency & Independence	<ul style="list-style-type: none"> • Adv. Building Systems • Adv. Propulsion Systems • Storage, Distribution, Conditioning & Transmission • Advanced Energy Generation
2	Environmental Quality	<ul style="list-style-type: none"> • Monitoring & Assessment • Remediation & Restoration • Pollution Avoidance & Control
3	Information Access & Communication Effectiveness	<ul style="list-style-type: none"> • Adv. Components • Data Comp. & Routing • Comm. Interop. & Parallel Procs. • Info. Management • Intel. Complex Adaptive Systems
4	Health Care & Agricultural Efficiency	<ul style="list-style-type: none"> • Adv. Biotechnology • Medical Devices & Equipment • Agricultural Production Efficiency • Food Supply Safety • Adv. Human-Machine Interface
5	Advanced Manufacturing	<ul style="list-style-type: none"> • Robotics & Automation • Adv. Processes • Semiconductor & Microdevice Mfg.
6	Improved Materials	<ul style="list-style-type: none"> • Alloys, Ceramics, Composites • Infrastructure • Stealth • Superconductors • A/C Structures
	Advanced Transportation	<ul style="list-style-type: none"> • Adv. Surface Vehicle Aerodynamics • Adv. Avionics & Control • Adv. Propulsion & Power Systems • Systems Integration • Adv. Human Factors & Life Support

⁴ White House Document, March 1995.

2.1.2 Facility Capability Assessment⁵

An evaluation of the capabilities of possible partners on the project was the other area of background work performed. Although the research and work performed would be accomplished primarily by the MIT students and faculty members, the project team had a wealth of resources available in the form of equipment and engineering experience throughout MIT's academic community, MIT Lincoln Laboratory, and Draper Laboratory. The team planned to use these other sources of knowledge extensively to further their design, so it was important to know what strengths and competitive advantages were possessed by the contributing partners.

In order to get a feeling for the different strengths of each institution, the research areas of the three units were examined. Each project was classified into one or more of the 'National Needs Bins' from the White House Report from Table 2. The sources of data varied slightly for each facility, so the following brief summaries of the sources lends some understanding to the depth and breadth of the research.

2.1.2.1 Charles Stark Draper Laboratory

The Draper Laboratory capabilities were identified by investigating both recent and current research projects. These projects were found in the unclassified Company Sponsored Research (CSR) and Independent Research and Development (IR&D) manuals, dating from Draper Fiscal Year 1992 to the present. Mainly, Draper focuses its research in two areas, though it does perform some level of work in each of the seven critical needs bins. The two main research areas were *Information Access & Communication Effectiveness* and *Advanced Transportation*. Draper also has competitive advantages in the area of *Advanced Manufacturing*, with emphasis on microdevice fabrication.

2.1.2.2 MIT Lincoln Laboratory

The primary areas of activity at the MIT Lincoln Laboratory was determined from articles published in the Lincoln Lab Journal since 1991. Each article was classified into one of the bins. In addition, each Journal contains a list of short abstracts of both recently published papers by Lincoln Lab employees and current Masters and PhD theses. Because of the number

⁵ The Facility Capability Assessment is taken with only minor modifications from the team's Priorities & Opportunities Document, delivered 23 October 1996.

of projects ongoing at Lincoln, only those judged to be most relevant were classified into bins. Work at Lincoln mainly consists of projects in the same area: *Information Access & Communication Effectiveness*. Projects in machine intelligence, adaptive optics, and advanced imaging all have influences from this field. Though a distant second place, *Advanced Transportation* is also an area of significant concentration at Lincoln. Their extensive work on air traffic control greatly contributed to this ranking. The Lab is also working in other areas including advanced computer processing and micromachining.

2.1.2.3 MIT Academic Community

The MIT Academic Community was evaluated in terms of departments: Aeronautics/ Astronautics, Electrical Engineering, Computer Science, Material Science, Mechanical Engineering, and Ocean Engineering. The Academic Community's capabilities were identified mostly by the current research projects in each of the departments.

A majority of the current research projects in the Department of Aeronautics and Astronautics deal directly with advanced transportation technologies. In addition to specific component research such as engine technology and aerodynamics, the department studies several aerospace-related issues. These issues include human factors, avionics, materials, and large-scale systems such as air traffic management.

Research in a broad range of subject areas characterizes the Department of Electrical Engineering and Computer Science. Since the department did not provide a current list of projects, information on its work was obtained from various research groups. These research groups covered topics ranging from nanofabrication to the study of language, speech, and hearing. In particular, the department has several laboratories exploring parallel systems architecture and human interface issues.

Many of the projects in the Department of Material Science are aimed at developing a better understanding of a specific material's behavior. Other projects investigate the role of materials in systems, such as corrosion of aircraft structures.

The Department of Mechanical Engineering is involved in a very diverse range of projects which illuminate the strengths of the department. Many projects deal with biomedical applications, such as motorized systems to restore a paraplegic's ability to walk. The department is also conducting a significant amount of research in robots, both for

manufacturing purposes and at a more basic level. Robotics also seems to have led to strong interest in control of robots and unmanned systems in the department.

The last MIT department surveyed was the Department of Ocean Engineering. Many of its projects involve simulation of fluid dynamics for ship and ship systems. The department is also involved in conducting some research in Unmanned Underwater Vehicles (UUV).

Relating these research areas to the White House Critical Needs Bins, the MIT academic community has research which addresses each of the bins. However, the most pertinent research dealt with the *Advanced Manufacturing, Improved Materials, and Advanced Transportation*.

2.2 Four Opportunity Areas

2.2.1 Brainstorming

With this substructure in place, the team next needed to identify possible areas where the most impact could be made in a two year period of time. The team began work with several brainstorming sessions designed to incorporate creativity into the design process. Although the team had the opinions of many key players in the aerospace industry, the objective was to determine a *new* solution to the recognized problems. The brainstorming sessions had only one rule: there were no bad ideas. Along with this regulation came the precept that no ideas should be ridiculed or denounced, no matter how outlandish or visionary.

At first, the team tried to limit the concept generation hierarchically. That is, the team first tried to generate significant areas of opportunity, which would hopefully lead to a specific genre of technology and finally to the perfect concept. However, this boundary really hampered the idea generation process, and the method was soon repealed. Ideas were generated without regard to their scope, their probability of conception, or real feasibility.

There were three different levels of brainstorming sessions. The first was a number of regularly scheduled meetings that included all the members and anyone who wanted to sit in and participate in the sessions. The second type consisted of mini-groups,. When certain ideas emerged that begged further exploration, these mini-groups were developed to explore the region of interest. Finally, the team members were individually tasked with generating ideas on their own to bring to the group meetings. These creative sessions led to literally hundreds of

new ideas, so many in fact that there was not enough time to critically analyze each.⁶ It should be noted, however, that the generation of new ideas gradually slowed and eventually seemed to reach a limit. The decrease in frequency of new ideas ultimately indicated that the team was ready to move to the next phase in the process.

2.2.2 Priority Grouping

The next phase of this opportunity generating process was to rate each idea on its perceived promise. This was somewhat difficult, though, since each of the ideas had a different scope. For instance, one brainstorming result was the need for a new Air Traffic Control system in the US--and throughout the world for that matter. Obviously, this kind of project is enormous in magnitude. On the opposite end of the spectrum, another conception called for the development of an amphibious engine for use in a submarine/airplane hybrid. This proposition was a very specific technology that would only influence a small sector in the marketplace.

With the difficulty of scope in mind, the team decided to rate each idea on a very general Low-Medium-High scale. Each team member ranked all of the ideas, and the aggregate rankings determined the ideas that seemed to offer the most opportunity for the team. It should also be noted that the team did measure each concept with respect to the project ideals presented by Draper (see Table 1: Elements of the Draper Charge). The purpose of this categorization was to limit the field of ideas for the team to sort through. At this point, there were just too many ideas presented to completely evaluate. By choosing a smaller set of most attractive ideas, the team could focus its efforts better. Therefore, only the top third of the ideas were evaluated.

2.2.3 Final Categorization

Referring back to Figure 2, the next step in the ideas generation process was the development of rationale for the rankings. Up to this point, there had been no concerted effort to list the pros and cons of each idea, since there were simply too many ideas to survey. However, the team felt it necessary to look at the positive and negative aspects of each of the designs.

⁶ To view the list of generated ideas in their entirety, reference Appendix E of the Priorities & Opportunities Document in the project library.

It is important to keep in mind that the whole thrust of this process was to identify *areas* of opportunity and not specific designs. However, many explicit designs had cropped up in the brainstorming process. At this time, the team needed to identify into which *areas* the most attractive ideas seemed to fall. These final higher ranked ideas seemed to naturally fall into four larger categories. These four opportunity areas were: Innovative Projectile Systems, Intelligent Cooperative Systems, Advanced Aircraft Navigation and Control, and Inexpensive Space Capability.

With the identification of these opportunity areas, the team then held subgroup meetings to further develop more concepts in each arena. For example, possible concepts under *Inexpensive Launch Capability* included developing a hybrid launch system that used balloon technology and a large rocket as a patched together small satellite launcher.

The result of this process was a review held at Draper to induce engineering expertise and critical thinking into the heretofore free-thinking process. At the review, these opportunity areas were presented with examples of possible concepts within that grouping. The Draper engineers concurred with the opportunity areas and encouraged the team to pursue market assessments in all four of the opportunity areas.

2.3 Market Assessment and Draper Selection

The outcome of most engineering efforts is supposed to be a system that can be sold by the manufacturer to an interested user. In order to ensure that the team was headed toward a marketable product, the team next began a phase in which the different opportunity areas and concepts were scrutinized for their marketability.

The team's first decision was to limit the research to the top remaining concepts. Due to the team's limited resources and manpower, only a few ideas could be evaluated meaningfully. The team finally chose five ideas:

- a tailsitting VTOL UAV,
- a hybrid launch system,
- a solar sail,
- an innovative projectile, and
- an autonomous search and rescue system.

These five ideas were thoroughly investigated to determine their individual worth to the team. For each, a preliminary engineering analysis was performed to validate the notion. Also, the team developed several missions for each system to perform. Finally, an introductory market assessment and crude cost estimate of the five final systems detailed each system's economic feasibility. The final outcome of this exercise was a Product Selection Matrix that was built in order to compare the designs to each other.⁷

The team was divided into subgroups for the analysis. The author specifically worked on the hybrid launch system, so its analysis is presented here as an example of the amount of examination each idea received.

2.3.1 Hybrid Launch Example

The Hybrid Launch System (HLS) idea was created to address the need for cheaper access to space. The need for more inexpensive launches is well-recognized in the space community, and it is generally accepted as a lucrative opportunity area for a significantly improved launch system. The HLS uses a high-altitude balloon to take a payload to 125,000 feet. At this altitude, a rocket would be launched from the balloon platform. The rocket could be optimized for the high altitude launch environment and could achieve a much better performance due to this optimization.

The preliminary analysis for the system listed the propulsive savings HLS has with respect to current launch systems. The altitude boost alone would account for nearly 750 m/s of propulsion at a typical booster I_{sp} . Also, HLS would avoid traveling through the thicker atmosphere near the earth and would save about 250 m/s just in not fighting that drag. HLS also could incorporate a nozzle optimized to the near vacuum atmosphere at 125,000 ft. Preliminary calculations showed that the I_{sp} could be raised from 240 sec to 300 sec on a typical rocket. Lastly, the system could be lighter since it would not have to fight the high stresses typical of launches in the lower atmosphere. This increases the payload mass fraction and decreases the launch cost per kilogram for a given system weight.

The technical challenges of HLS were also identified. First, the maximum payload of the system is limited by balloon technology. Presently, the largest payloads taken to high altitudes by balloons are about two metric tons. Another technical challenge is making a

⁷ For clarity, this matrix is intentionally left out by the author. The Product Selection Matrix can be found in the Market Assessment Document, prepared by the team in January 1997.

balloon which could stand a vertical launch. Whether it self-destructed or had a channel for the balloon to lift through, this concept has never been done before and would probably make for a difficult manufacturing job.

As promised, a cost analysis was performed. The competing systems would be the Pegasus rocket and some newer small rockets still in the development stage. Pegasus launches cost around \$15 million, while AeroAstro Corporation claims it will soon have the capability to launch 250 lbs for \$6 million. The cost of the system must then be competitive with these smaller launch vehicles.

For each concept, potential customers were polled to assess the usefulness of the idea. For HLS, the customer reaction was mixed. Professor Jack Kerrebrock indicated that many people were skeptical of the launching from a balloon platform because of its unreliability. On the other hand, reliability might not be as important a feature in the future of satellites. Many satellite constellations are building smaller and less expensive satellites and it is therefore more economically reasonable for the manufacturer to build contingency satellites and use a cheaper and less reliable launch system. The customer survey did unearth a negative reaction from the project manager of a group in Alabama that is trying to use the same concept to launch hybrid rockets. This manager described the many technical challenges that have arisen during their project development and felt that the concept was not economically viable.

In order to make sure that the projects were evaluated objectively, a Product Selection Matrix was developed to show how well each proposal fit some criteria that characterized a desirable system. Table 3 shows the criteria and how well HLS met those criteria.

A similar assessment was performed for each of the systems, but the rest are left out for the sake of brevity. The team then used these market assessments to downselect to a final system. By comparing all of the different systems and how well each system met the criteria listed in the Product Selection Matrix, the team ranked all of the systems according to which system seem best suited for the team. The team chose the Solar Sail as its favorite, probably because most of the team members were more comfortable with a space-based design.

Table 3: Product Selection Matrix Criteria

<i>Criterion</i>	<i>HLS Rationale for Criterion</i>
National Need	There is certainly a need to develop a method for sending small payloads into orbit at a relatively inexpensive price.
Matched to Organizational Capabilities	Draper does not do much work in rockets, but MIT does have some expertise.
Project Public Appeal	HLS would have appeal if it could significantly reduce launch costs.
Uses Unique/World Class Capabilities	No new technologies would have to be developed. However, the integration of the needed technologies would need experts like those at MIT and Draper.
Matched to Student Team Capabilities	Many of the students have worked on space projects in the past, some even with rockets.
Student "Fun Factor"	This project would provide the opportunity for the students to get involved with the entire concept design and production.
Difficult for Competitors	This design would not be any more difficult for competitors than it would be for this team.
Best Market-Product Type Quadrant	This product is in the most risky quadrant: a new technology front that would be market to new customers.
Market Breadth	HLS spans both the military and civilian markets, and would appeal both domestically and abroad.
Prototype Scale/Time Capability	One of the benefits of not developing any new technologies is that the system can be designed and built in two years.
Growth Potential	Draper does not have the facilities to mass produce these systems, but technical alliances could be formed.
"Unobtainium"	The development of a highly reliable launch system is never trivial. Also, thrust vector control and balloon launches are untested fields.
System-based product	This system requires integration with a customer's space vehicle, a ground station, and the current system.
First-of-a-kind	None of the technology used is new, but the integrated package would be novel.
Real Benefit Identified	The benefit of this system is cheaper access to space.
Cost Estimate	HLS could be built for less than \$6 million.
Patent Search Performed	No concept has yet been patented.
TELTEK Assessment Performed	Not performed.
Preliminary Engineering Analysis	The analysis is described in the previous section.

2.3.2 Draper Selection Meeting

The team took these results back to a team at Draper to again incorporate feedback into their design process. While the team felt like it had made an objective choice, the feedback

from Draper would serve as a safety valve to increase the objectivity of the choice. Plus, Draper was funding the project and therefore deserved the chance to steer the work of the project to the areas in which the Lab felt most comfortable.

After presenting the market assessments for each concept, the team briefed Draper about how the systems were rated relative to one another. The team also showed Draper the final rankings of the systems that implied the most desirable projects from the team's viewpoint. A panel of engineers and marketers then broke away from the group to evaluate the concepts on the merits of the market assessments and preliminary engineering results. This panel returned with a decision from Draper: continue work on the Innovative Projectile and Tailsitter. This decision startled the team, since their own rankings were seemingly disregarded. (The Innovative Projectile and Tailsitter were ranked #3 and #5 out of the five systems.)

In retrospect, this feedback was necessary. The panel from Draper performed its function and returned an objective decision based on the merits described in the market assessments. While the Solar Sail seemed impressive to the team, the Innovative Projectile and Tailsitter were probably more suited to the technical advantages of MIT and Draper. Objectively, these projects were the most promising and therefore deserved the undivided attention of the team.

The team immediately decided to narrow the project to the Innovative Projectile, since the team was not large enough to develop two designs simultaneously. The rest of this thesis will detail the design of the Innovative Projectile.

3. Requirements Analysis

Any valid set of technical requirements must be derived from the needs of the customer. This assignment was problematic, though, since the final customer for the project is not known. Draper's charge to the team was to meet one of the national aerospace needs of the country. Theoretically this meant that eventually there might be many customers each with slightly different requirements for the same kind of concept.

With this in mind, a select group of team members and Draper engineers determined a set of parameters that might describe a highly marketable smart projectile.^{8,9} These parameters became the baseline of needs used by the team to determine the technological requirements needed by the projectile. The team named the projectile Wide Area Surveillance Projectile (WASP).

The requirements document¹⁰ revealed many probable needs of a customer for an intelligent projectile. The team took these requirements performed several activities to determine the direction these requirements pushed the design. The team formed some mission scenarios to attempt to characterize which missions for which the projectile seemed ideally suited. Also, the team performed a functional analysis and made a quality table to further define what the most important requirements would be. Lastly, the team contacted military officials and incorporated their feedback on the initial set of requirements into each step. These activities occurred basically in parallel, and the output of one analysis feeding iterations of other analyses.

Through the course of these investigations, the team solidified a new set of customer requirements and assigned an importance weighting to each requirement, as shown in Table 4.¹¹ Weights were given to each of the customer needs to reflect how important each of these needs were with respect to each other. For example, both a *Long Loiter* and a *Long Shelf Life* were deemed necessary, however, the range was considered much more important than the

⁸The actual group consisted of Charlie Boppe, Prof. John Deyst, and John Elwell of Draper Lab.

⁹ The title of the requirements document refers to the projectile system as *Low-cost Intelligent Surveillance Projectile (LISP)*, which was the first name of the project. The name was later changes to *Wide Area Surveillance Projectile (WASP)*.

¹⁰The requirements document can be found in Appendix C

¹¹ For a more detailed discussion of the transition from initial requirements to final derived requirements, see the thesis of Josh Bernstein, *System Design for a Rapid Response Autonomous Aerial Surveillance Vehicle*, June 1997.

shelf life of the vehicle. Therefore, the range was weighted heavier than the shelf life--10 to 4 respectively.

Table 4: Derived Customer Needs

<i>Customer Need</i>	<i>Weight</i>
Long Range	5
Long Loiter	10
Long Operational Time	10
Max Field-of-View	8
Max Image Resolution	8
Acc Image Position Determination	9
Min Self Destruct Debris	4
Low Cost	10
Near Real-Time Info Processing	9
High Degree of Autonomy	8
Long Shelf Life	4
Strong Stealth Characteristics	5
Ease of Operations	10
Ease of Maintainability	9
High Reliability	8
High Extensibility	5
Short Launch Time	3
Very Safe	10

3.1 Requirements Quality Function Deployment (QFD) Build

These relative weights allowed us to use a development tool called a Quality Function Deployment (QFD).^{12,13} In general, a QFD is a matrix representation of the customer needs charted against the technical requirements needed to achieve those perceived needs. Usually, the customer needs are determined by talking with potential customers and industry leaders or by market surveys and literature searches. The technical requirements are best determined in a brainstorming session with a group of people knowledgeable of the design and the proposed industry. Each customer need can be evaluated individually, and a sublist of requirements can be made for each. Combining the sublists and eliminating repeated or similar requirements,

¹² According to Notes from an MIT aerospace design course taught by Charles Boppe, 16.870, the history of the QFD matrix began around 1972 when Prof. Mizono of the Tokyo Institute of Technology developed Quality Tables for the Kobe Shipyards. This method was later expanded by Hauser & Clausing in the Harvard Business Review, May-June 1988.

¹³ The QFD matrix is known as the "House of Quality" because of its shape. Reference Appendix A for the QFD matrix developed by the team for the Innovative Projectile.

then, provides a complete list of the needed technical requirements. Ordinarily there are several times as many requirements as there were customer needs.

Technological Requirements		Customer Needs						
		Importance	Low inert mass fraction	Efficient aerodynamic design	Lightweight materials	High energy density	Flight path control	Efficient on-station propulsion
Long range	5	9	9	9	9	3	9	9
Long loiter	10	9	9	9	9	9	9	9
Long operational time	10	3	3	9	9	3	3	
Maximum field of view	8						1	3
Maximum image resolution	8						1	3
Acc. image pos. determination	9						1	
Minimum self-destruct debris	4							3
Low cost	10	3						
Near real-time info. processing	9							
High degree of autonomy	8	1				3	3	1
Long shelf life	4							
Strong stealth chars	5				3			1
Ease of operations	10				1		3	
Ease of maintainability	9							
High reliability	8							
High extensibility	5	3	3	3	1	3	3	
Short launch time	3							
Very safe	10							
Technical Importance	7837	218	180	265	224	169	236	122
		9	6	10	8	6	8	4
Objective Target Values		0.2	23:1 glide slope	carbon-fiber	400 Whr/kg			

Figure 3: Sample of QFD for WASP

After the customer needs and requirements lists are compiled, the next step is to evaluate the amount each requirement supports each customer need. This is accomplished by assigning a metric to each interrelation. Typical values for the rankings are 9 for a strong connection, 3 for moderate connection, and 1 for a weak connection. These values fill out the

body of the matrix to show the relationships between different needs and customer requirements. As an example, the technical requirement of *Efficient Aerodynamics* in Figure 3 obviously is related to the customer's need of *Long Range* and therefore would receive a score of 9. But *Efficient Aerodynamics* could also mean a *Long Operational Time* and therefore receives a score of 3 for that customer need. On the other hand, *Efficient Aerodynamics* really has little or no bearing on *High Reliability* or *Strong Stealth Characteristics*, so it would not receive any score for those needs.

After the matrix is filled in, the technical importance of each requirement with respect to the entire set of customer needs can be determined. This was done by summing the products of the correlation coefficient and the importance weighting of the customer need. Continuing the same example from above and referencing Figure 3, *Efficient Aerodynamics* scored 9 for both *Long Range* (relative importance of 5) and *Long Loiter* (10), while it also scored 3 for *Long Operational Time* and *High Extensibility* (worth 10 and 5 respectively). The sum for the technical requirement *Efficient Aerodynamic Design* is 180.

Notice, however, that this technical importance has no real value by itself and that only relative values are important. In one matrix, this might be the highest score. In another, it could be the lowest. In order to give some meaning to the value, the technical importance is normalized by the largest technical importance in the matrix. This largest value receives a relative importance of 10. Technical requirements whose importance sums to within ten percent of the maximum receive 9. Those within twenty percent receive 8 and so on until all of the requirements are ranked. Again referring to Figure 3, the maximum value in the matrix happens to be for *Lightweight Materials*, a technical importance of 265. Because the 180 of *Efficient Aerodynamic Design* is 32% removed from the maximum, the relative importance of the technical requirement is 6.

The final metric provided by the QFD matrix is a visual warning of the conflicts that are present between the different criteria. In the roof of the House of Quality, a circle designates a possible future conflict between technical requirements. In Figure 3, the only conflict shown is between *Efficient Aerodynamic Design* and *Minimize Component Size*. The conflict between requirements would arise if the most efficient aerodynamics dictated larger actuators, wings, or tail surfaces than the absolute minimal componentry.

For WASP, the team determined 51 technical requirements from the list of 18 customer needs. These are obviously too numerous to list, but Appendix A has the final QFD matrix which lists all of them.

3.2 QFD Matrix Results

From the QFD matrix, the team determined which of the technical requirements would be most important to fulfill (see Table 5). In the end, the team would have to account for all of the technical requirements. Most requirements would have to be fulfilled. The team would have to have strong reasoning for any requirements that could not be met. The matrix was made in order to give some background for the inevitable trades that would have to be made as the project progressed.

Table 5: Top Technical Requirements

Technical Requirement	Technical Importance	Relative Importance
Flight System Disturbance Rejection	265	10
Lightweight Materials	265	10
Wide Bandwidth Communication	245	9
Robust Power System	245	9
Robust Shell	237	9
Efficient On-Station Propulsion	236	8
Light Sensor System	228	8
Low Subsystem Power Requirement	227	8
High Energy Density	224	8
High Data Throughput	220	8
Low Inert Mass Fraction	218	8
On-board Intelligence	202	7
Maximize Automated Functions	201	7
Accurate Navigation	198	7
High Design Commonality	195	7
COTS/Standard Components	195	7
Minimal Mechanical Systems	195	7

Notice in Table 5 that the two most important technical requirements are *Flight System Disturbance Rejection* and *Lightweight Materials*. The *Flight System Disturbance Rejection* is listed first with the assumption that a number of requirements are affected by the stability of the loitering craft. *Lightweight Materials* had a high relative importance rating because of their effect on a large number of the aerodynamic and flight performance criteria encompassed in the Customer Needs.

Probably the most important aspect of the QFD is that it forces a need-based design: Customer needs drive technical requirements; technical requirements drive subsystem requirements; subsystem requirements drive component selection; component selection drives manufacturing processes. The underlying, fundamental base of the entire design is the customer needs. As many needs as possible are fulfilled, but no extraneous (and therefore inefficient) functions leak into the final design. From a systems point of view, this need based approach is a good practice.

3.3 Functional Flow Diagram

With all of the input gathered from Draper engineers, DoD contacts, and the QFD analysis, the team had a fairly firm idea of the functions this system was to perform. It was then appropriate to try to solidify this system functionality in the form of a Functional Flow Diagram (FFD). This FFD would give the team a metric to develop different system variants. With each variant, the functionality of the system represented in the FFD would have to be retained. Capabilities performed by the system that were not included in the FFD would be considered extraneous and useful only if the extra benefit to the user did not inhibit the rest of the design.

The FFD in Appendix B shows this functionality. It was evident from the diagram that all of the necessary customer requirements were retained. (Later, some variants would fail to perform all of the functions in this diagram, thereby limiting their usefulness.)

3.4 System View

It is appropriate at this point to step back and evaluate the chosen system as a whole. The piece of the system that loiters over a remote area and returns surveillance information will remain the author's focus for the majority of the rest of the paper. The flyer is only one part of an entire system that must function simultaneously in order to provide a useful product to the customer.

3.4.1 Baseline Mission

With the FFD, the team next detailed the baseline mission, shown in Figure 4. A projectile is launched from a remote site encased in a projectile casing. After a ballistic cruise to the desired destination, the projectile decelerates, despins, and deploys into the loitering

vehicle. This loitering vehicle surveys an area of interest for as long as possible, then self-destructs.

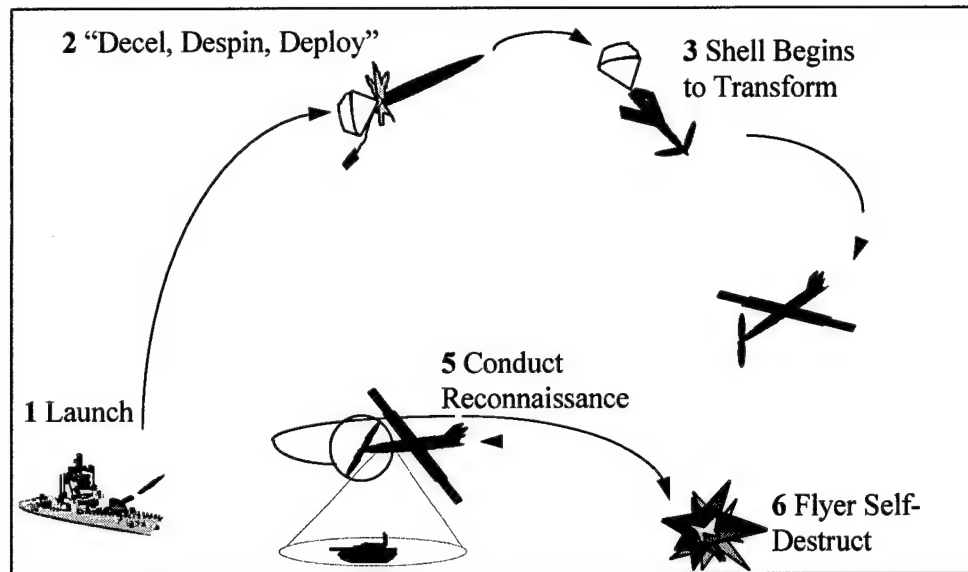


Figure 4: Baseline Scenario

3.4.2 System Architecture

The baseline mission detailed above needs many components to be viable. The team therefore developed the different elements that would be necessary to achieve this mission. These elements of the system are shown in Figure 5. In the figure, the elements between the dashed lines are elements of the system, while those outside the dashed lines are external interfaces with which the system must operate.

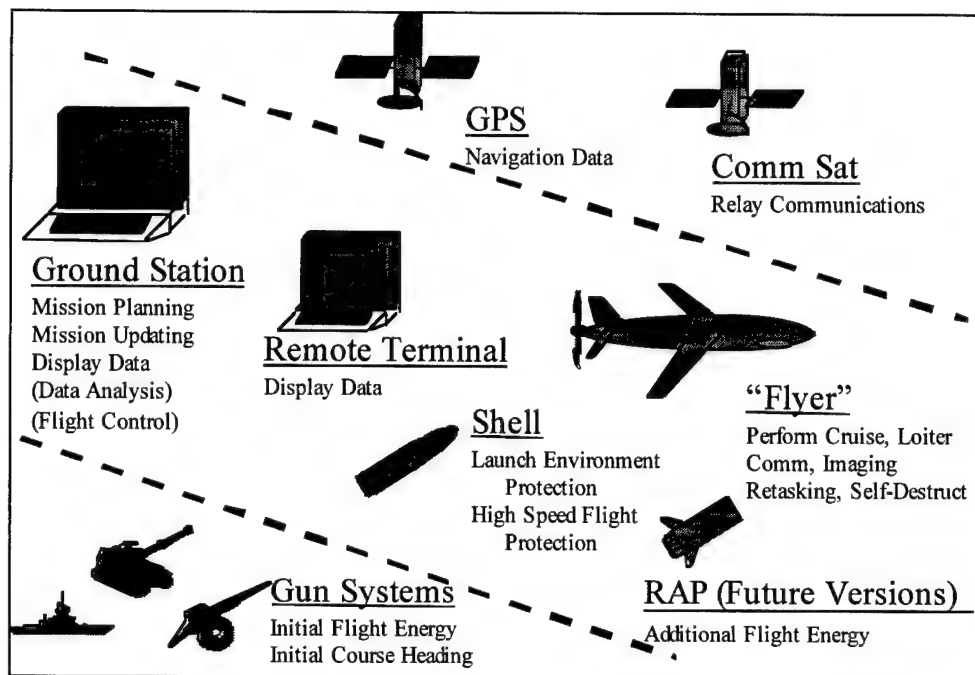


Figure 5: Top Level Systems Architecture

3.4.3 Mission Scenarios

The team recognized the fact that the more missions this system could perform, the lower the cost of the vehicle would be when amortized across these different scenarios. Using the FFD, the team decided to attempt to derive a set of mission scenarios in which WASP might be useful. Initially, three classes of scenarios were identified: long duration missions, information systems missions, and short duration missions.

The long duration missions assumed the vehicle would be able to loiter on station for more than four hours and that an imaging or radar-type surveillance sensor would be the payload. The first mission recognized was called *Area Reconnaissance*. In this mission, the system would be deployed to survey the largest area possible while aloft. The second mission was *Long Endurance Reconnaissance*. For this mission, the system would loiter over a desired location for as long as possible. The last mission in this class is *Route Reconnaissance*. In this capacity, the system would fly ahead of a moving entity to provide an alert of any impending dangers.

The information systems missions extrapolated the system capabilities to those available with unique kinds of payloads. The *Signals Intelligence* mission requires that the flyer carry a payload that could intercept and translate electronic signals. Signals Intelligence (SIGINT) is a growing and important thrust in today's military, and this mission would be attractive to DoD. The other information systems mission is *Communications Relay*. This mission of the system provides a temporary but mobile communications link for a deployed unit. If line-of-sight communications are unavailable, this system would provide an alternate link.

The short duration missions are characterized by a short vehicle operational time. Four possible missions were identified. In the *Company-Level Reconnaissance* role, the system would provide the ability to look over the next hill or into the next town. The system could also be used for *Damage Assessment*. Many of today's weapon systems have the ability to target objects well beyond a visible distance. Mortars or tanks could use this vehicle to determine whether or not an attack was successful. A third short duration mission was to be a *Hunter*. In this role, the system would be equipped with the ability to identify a target and attack that target with an on-board weapon. It should be noted that this mission was found to be quite visionary and there is no way in the near future that all these capabilities will be grouped together on a system small enough to be launched from an artillery piece.

4. Preferred Product Selection

The next step in the design process was to use the QFD and FFD as a foundation to develop some concepts of the system. This was important to give a more definite plan to the design and to give some engineering analysis to the idea. In order to perform the analysis on a more complete set of design possibilities, the team developed three variants of the system, each of which should be able to satisfy the functionality of the system.

4.1 Three Variants

The three variants are known to the team by nicknames which describe what makes one idea different from the others. The first, "Supershell", transformed from a simple projectile-like form into a more complicated flyer. The second used the existing design for a projectile and designed a flyer that could be extracted from the inside of the projectile. This design was named "Silent Eyes" after a similar program proposal in the DoD. The last concept was named "Twin Shells" and contained two vehicles in the same projectile that each carried a subset of the system functionality.

Taking these original loose descriptions of the system, the team proceeded to further develop ideas by trying to fit components into each of the designs to show that they could indeed perform the specified requirements. A FFD and SBD specific to each variant were also developed to further advance each of the designs to a state where a reasonable choice could be made.

4.1.1 Supershell

As detailed in Figure 6, Supershell used the projectile shell as the body of the flyer. During the launch and ballistic flight, the shell would maintain the look of a normal projectile. At the end of this flight the projectile would deploy a parachute to slow down from the supersonic cruising speed to a lower dynamic pressure deployment speed. Supershell then would deploy its wings and tail from their stowed position. Also, a propeller would unfold from its packed position at the front of the projectile in order to provide thrust to the vehicle. After gathering and transmitting the sensor data during its useful flight envelope, the flyer would self-destruct before falling to the ground.

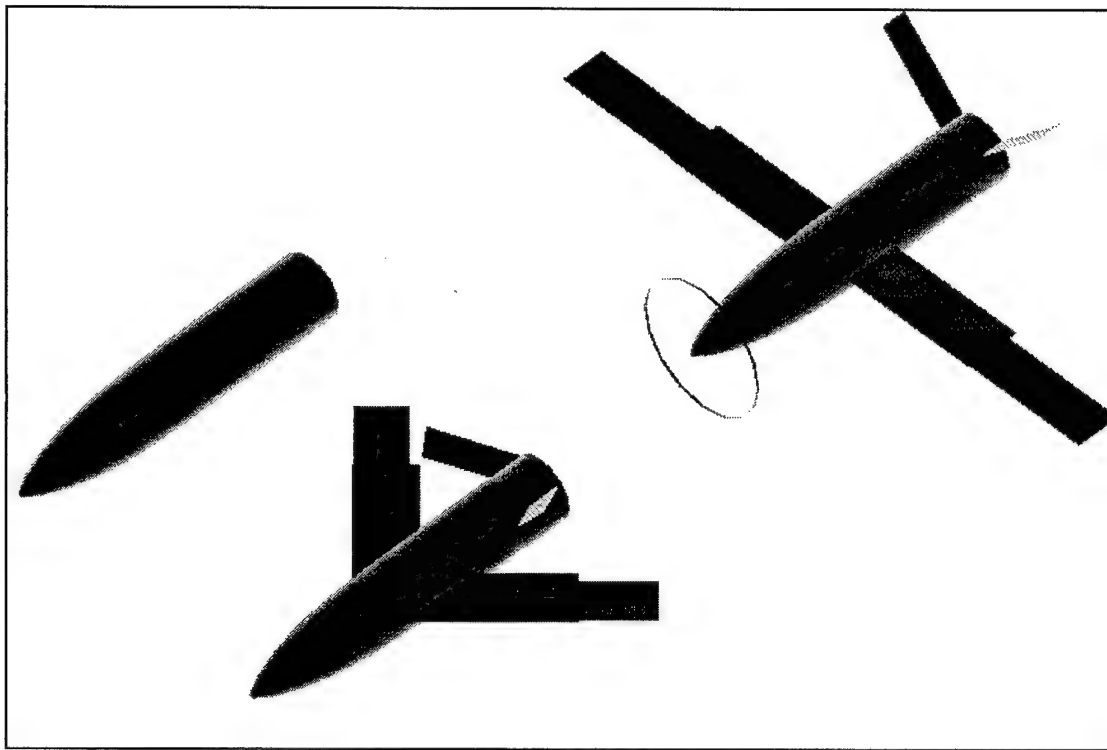


Figure 6: Supershell

This functional development led to several characteristics of Supershell that made the design interesting. Analysis of the flight characteristics of the vehicle showed that the shell would have to be made of some kind of composite in order to both survive the launch environment and also be light enough to allow the projectile to fly during the loiter period of its mission.¹⁴ According to experts in the field, the idea of using composites for projectiles is one that has not yet been fully explored. Therefore, using composites in this way would enhance the entrepreneurial and unobtainium aspects of the project.

The chief difficulty with Supershell is that this design is the most difficult to keep aloft for the mission. Though composites will greatly reduce the mass of the flyer, there is a delicate balance between reducing the weight of the material and hindering the projectile's ability to handle the g forces it will experience on launch.¹⁵ The aerodynamics group found even the

¹⁴ See thesis of David Iranzo-Greus, Rapid-Response Surveillance System Design and Aerodynamic Modeling, for a more detailed description of the aerodynamic analysis done on the different variants.

¹⁵ See thesis of Cory R. A. Hallam, MIT/Draper Technology Development Partnership Project: Aerodeceleration, Structures, and Systems Design of a High-G, Rapid Response, Deployable Unmanned Aerial Vehicle, for further structural analysis and composite use for Supershell.

lightest configuration produced by the structures group was heavy enough to make the thirty minute loiter time a challenging requirement. Beyond the weight of the vehicle, is the boxy shape of the fuselage. Also, the original design did not have the typical projectile boat-tail, which made the drag coefficient much larger than in a typical aircraft. These aerodynamic considerations make the design difficult to keep aloft for the desired thirty minutes.

4.1.2 Silent Eyes

The next variant was based on using projectiles that were already present in the DoD inventory. The concept called for placing the entire flyer inside of the projectile and drawing it out after the ballistic phase of the mission. This variant, shown in Figure 7, was nicknamed Silent Eyes, after a proposal from DoD for a similar system.

Originally, this variant was to deploy out of the front of the shell. This method would allow the team to base the design of the most common shells in the US DoD inventory. In fact, many of the 5 inch shells have threads in the nose of the projectile and a hollow core, so that the same projectile can carry different payloads. Ideally, then, Silent Eyes would be compatible with this kind of arrangement, and could be screwed into existing shells.

Soon into the integration of this vehicle, it became evident that the only way to have a reasonably sized vehicle was to blow off either all of the cone shaped part of the nose or the rear of the projectile. Either situation presents the same problem, so the subgroup elected to eject the flyer through the rear of the projectile akin to presently functioning projectile systems. After ejecting from the outer shell, the flyer would then deploy its wings and tail to begin the loitering phase of the mission.

Silent Eyes did not have room for propulsion, so the aerodynamic design had to accommodate a glider. While this was not functionally important, the lack of propulsive capability would later affect the usefulness of the design.

One final important aspect of Silent Eyes was that it failed to self-destruct the outer shell after the flyer was ejected from it. Since this violates one of the system requirements, the design was tagged as lacking the required functionality of the system. Therefore, the only way Silent Eyes could be considered on the same level as the other variants was if it were such a superior choice that the team could reason with the customer to alter the self-destruction requirement.

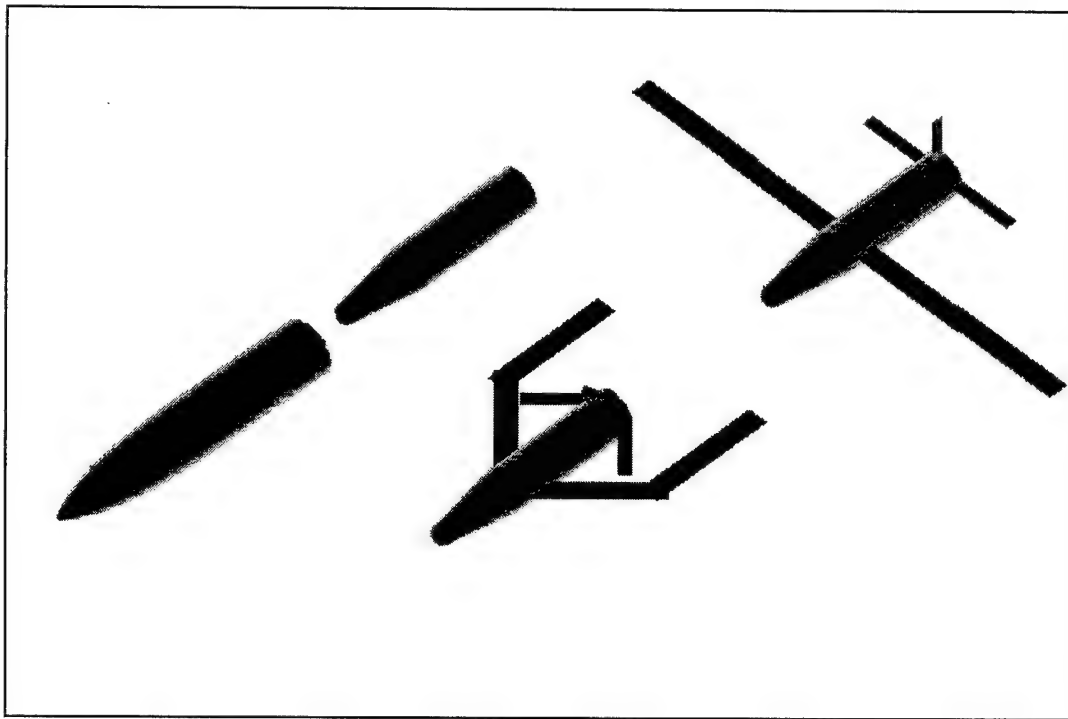


Figure 7: Silent Eyes

4.1.3 Twin Shells

The last variant developed at this time, Twin Shells, basically called for two different flying vehicles in the same projectile (see Figure 8). The initial advantage to this system is that it accounts for the LOS communication problem not addressed by the previous two designs. By deploying one flyer at the intelligence gathering scene and the other at some convenient intermediate point, the system would be able to communicate over nearly any terrain. Conceptually, one vehicle would carry only the imaging gear and a UHF antenna (or the equivalent) capable of sending the data to the second vehicle. The other vehicle would contain any on-board processing, control software, and navigation capability.¹⁶

¹⁶ The team also briefly considered deploying a balloon carrying a transponder to accomplish the data link, but the space required to contain such a system proved to be too large with respect to the total volume in the vehicle.

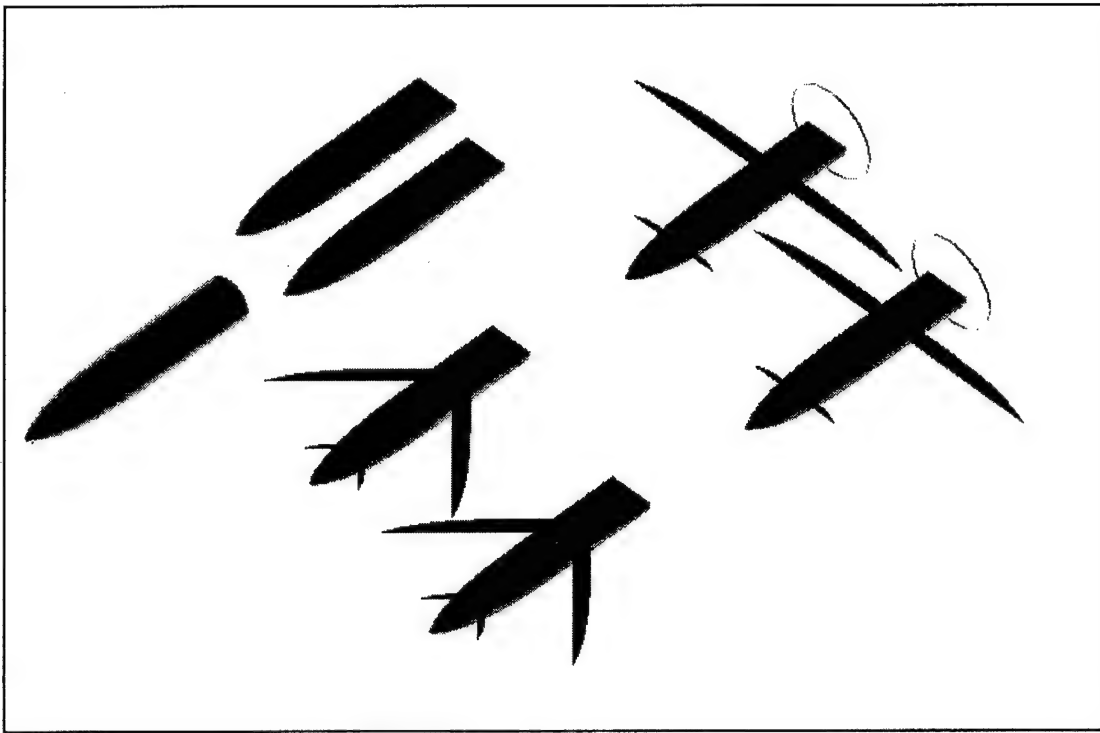


Figure 8: Twin Shells

The obvious difficulty of this concept was that many of the systems would be needed in both flyers. Navigation equipment, a transmitter, propulsion, and wings were components that neither vehicle could do without. For some of the components, off-the-shelf (OTS) components did not exist that would fit into the volume, so the design called for the development of some new technologies.

Furthermore, the complexity created by trying to develop two systems that functioned simultaneously and were dependent on each other to perform correctly proved to be nearly impossible. For example, there was not room on both vehicles to have a fully operating GNC system, so the design called for only one vehicle to carry a GPS receiver. The second vehicle was to determine its position from its knowledge of the first vehicle's position and its own relative position to the first vehicle. These kinds of problems quickly made the design extremely complex.

These complexities considered, Twin Shells was developed alongside of the other variants. In the comparison of concepts, these intricacies would hurt Twin Shells, but the idea was intriguing enough to carry into the selection discussion.

4.2 Selection Matrix Criteria

Each of these three variants had attractive features and adverse aspects. In order to decide which variant should be chosen as the final design for the system, the team needed to develop some criteria to distinguish the different designs. Of course, there are numerous criteria that could be used to measure the designs, so the team first had to develop a set of criteria that would be manageable while addressing the most important customer needs.

Since the team's ultimate objective was to maximize the customer's satisfaction with the end product, the logical foundation for these criteria was the customer requirements derived as soon as the product concept was introduced. Also taken into account were the technical requirements that flowed to the top of the QFD analysis. Together, these requirements would be a good basis for developing a proper set of design criteria.

While developing these design criteria, it was important to not allow the human element crept into the design process. In fact a goal while developing criteria was to erase any bias that would impact the final decision. It should be noted that up to this point, the team was divided into subgroups to develop the three different designs. Each subgroup had time invested, hence bias, into each of the designs. Thus, it was the hope of the team to make the decision based only on concrete and relevant criteria that would not intentionally favor any one of the designs. Though this human element did not seem to affect the project at this point, the team was aware of the possible influence and strove to avoid it.

The final set of criteria developed can be found in Table 6. When viewing the table, one should take note that some of the criteria have negative weights. This implies that *more* of that particular metric hinders the attractiveness of the design. The first criterion, *Cost*, is a perfect example: a higher cost is less attractive than a lower cost.

Also note that all of the weighting magnitudes are greater than 5. At first, it might seem that the weightings should be more distributed over the entire range of possible values (in this case, -10 to 10). However, if a criterion weighting was too small, the effect of that criterion on the decision would likely be small. Therefore, the team was really looking only for criteria that would impact the final decision the most.

Table 6: Selection Matrix Criteria

Criterion	Unit	Weight	Notes
Cost	\$\$	10	<ul style="list-style-type: none"> The mid-range cost estimate for each design. Cost is the most important driver, so the cost had the highest magnitude weight.
Loiter Time	sec	10	<ul style="list-style-type: none"> The time the flyer could stay aloft and below 1000 m, according to the aerodynamic approximations for the design. The altitude of 1000 m was chosen since the imaging gear will not be nearly as useful above that altitude. A longer loiter time increases the number of missions one system can do, therefore loiter time also received the highest magnitude weight.
Inert Mass Fraction	unitless	8	<ul style="list-style-type: none"> The fraction of the total mass not encompassed by the payload or the fuel. This metric was developed to give a sort of mass efficiency for the design.
Surveillance Area	km ²	8	<ul style="list-style-type: none"> The amount of area that surveyed by a common imaging system on board the flyer while in the airspace 100 m above the target and no higher than 1000 m. Because the true mission of the projectile was to gather intelligence, a design that could cover a larger area would be more useful.
Component Technology Availability	N/A	8	<ul style="list-style-type: none"> A subjective measure of the amount of technology on the flyer that was currently available to the design team. This metric was used to factor into the design decision the amount of risk that the team would face due to a certain design.
System Complexity	N/A	-7	<ul style="list-style-type: none"> A subjective measure of the amount of complexity the final system would have. This benchmark would provide a sense of the risk due to the amount of new components the design required.
Deployment Scheme Complexity	N/A	7	<ul style="list-style-type: none"> A subjective measure of how difficult the deployment of the loitering craft would be.
Electrical Power Volume Available	cm ³	7	<ul style="list-style-type: none"> The amount of volume left over in the system after all the other components were located to be filled with batteries. All of the designs were very power limited, so this standard would rate how well each design could pack extra power.
Lift-to-Drag Ratio	unitless	6	<ul style="list-style-type: none"> The ratio of lift to drag produced by the aerodynamic design of the vehicle.
Flyer Range	km	5	<ul style="list-style-type: none"> The distance the flyer could travel after deployment into the final flying configuration. This range was meant to determine which design would have the most capability to survey multiple targets on the same mission.

With these criteria in hand, the team proceeded with an objective look at the different decisions. It should be noted that the process of creating these criteria was iterative. That is, the team first developed some of the criteria, tried to apply them to each of the designs, decided

that not every feature was encompassed by the set of criteria, and then revised that set of measures.

4.3 Selection Results

4.3.1 Inside the Matrix

The next obstacle for the team was to interpret these criteria with respect to the different designs. In order to provide the most objective look possible, the team developed a matrix: the criteria marked the rows and each variant had its own set of columns. Figure 9 shows the completed matrix.

In order to get a relative score for the designs, the team chose Silent Eyes as the baseline design. This seemed legitimate since Silent Eyes was based on using the projectiles in the current DoD inventory and required no propulsion. The other two designs, then, would be rated by whether or not they outperformed Silent Eyes for each of the given criteria. This comparison was accomplished and the results are in Figure 9.

The values for each of the designs in Figure 9 are shown in the first column for each variant. These values were compiled by the subgroups that prepared the component layout for the variant. These numerical values were then normalized by the performance of Silent Eyes on that criterion. To take an example from the matrix, the *Flyer Range* of Silent Eyes, Supershell, and Twin Shells were 19.9 km, 58.1 km, and 37.7 km respectively. These translated into comparative scores of 2.92 for Supershell and 1.89 for Twin Shells. (The comparative score for Silent Eyes was always 1.) This can be interpreted as Supershell having nearly three times the performance of Silent Eyes for this criterion and Twin Shells performing almost twice as well.

These comparative scores were in turn multiplied by the criterion's weight. This was done to account for the principle that all criteria were not equal, and that some warranted more influence than others on the final decision. Also, this allowed for counting some of the factors as positive contributors and others as negative influences. Continuing the same example from above, the weight of *Flyer Range* was 5, so the weighted score for Supershell was 14.62, while Twin Shells received a 9.47.

Measure	Units	Weighting	Silent Eyes				Supershell				Twin Shells			
			Numerical Value	Comparative Score	Weighted Score		Numerical Value	Comparative Score	Weighted Score		Numerical Value	Comparative Score	Weighted Score	
Cost	dollars	-10	39520	1	-10		72205	1.83	-18.27		163045	4.13	-41.26	
Loiter Time	seconds	10	830	1	10		1358	1.64	16.36		721.5	0.87	8.69	
Inert Mass Fraction	-	-8	0.97	1	-8		0.98	1.01	-8.08		0.99	1.02	-8.16	
Surveillance Area	square kilometers	8	19.5	1	8		48.2	2.47	19.77		34.8	1.78	14.28	
Component Technology Availability	subjective	8	9	1	8		7	0.78	6.22		3	0.33	2.67	
System Complexity	subjective	-10	4	1	-10		7	1.75	-17.50		10	2.50	-25.00	
Deployment Scheme Complexity	subjective	-7	3	1	-7		5	1.67	-11.67		9	3.00	-21.00	
Electrical Power	cubic	7	198	1	7		259	1.31	9.16		144	0.73	5.09	
Volume Available	centimeters	6	22.5	1	6		19.9	0.88	5.31		19.9	0.88	5.31	
Lift-to-Drag Ratio	-	5	19.9	1	5		58.1	2.92	14.60		37.7	1.89	9.47	
Flyer Range	kilometers	5												
Total Score					9				15.90				-49.91	
Relative Score					1				1.77				-5.55	

Notes:

- The Glider variant did not have space for a self-destruct mechanism, so such a device was left out. This omission means that the design does NOT meet all of the requirements for the system.
- For the Twin Shells variant, the mass listed is the total mass for both vehicles.

Figure 9: Selection Matrix

In order to determine the complete design performance, the weighted scores for each variant were summed over the entire set of criteria to achieve a total score for each variant. Silent Eyes' total score, it follows, was just the sum of the criteria weights, or 9.0. Supershell finished slightly ahead at 15.90 and Twin Shells at -49.91.

Finally, to make the scores even more relative, these total scores were then normalized by the total score of Silent Eyes. The final relative scores can then be thought of as how much the given designs outperform Silent Eyes. According the Selection Matrix, Supershell outperforms Silent Eyes and Twin Shells is a comparatively worse concept.

Some additional observations can be made about the matrix. For Supershell, the three most positive contributions came from a long *Loiter Time*, a large *Surveillance Area*, and a long *Flyer Range*. All three of these criteria are more or less based on the aerodynamic properties of the flyer, which were pronounced decidedly poor in the first analysis. It turns out that Supershell had enough extra volume available so that it could store the most fuel of any design, which allowed it to outperform the other schemes.

Another interesting feature of the matrix is the criteria which dragged down the total score of Twin Shells. *Cost*, *System Complexity*, and *Deployment Scheme Complexity* all significantly decreased the system's score. All of these criteria deal in one way or another with how elaborate the scheme was perceived to be. This result might have been anticipated because designing two vehicles into the same volume that otherwise would contain only one vehicle is conceptually much more involved.

4.3.2 Outside the Matrix

It is clear from the matrix in Figure 9 that Supershell was the most attractive choice. Also, it became obvious that Twin Shells was a less desirable concept than either of the other two designs. However, when this matrix was first constructed, this choice was not so clear.

In a team meeting called for the sole purpose of picking the final design, the first edition of this selection matrix was much less definite as to the best choice. Though Twin Shells still stood out as the obvious worst choice, Supershell and Silent Eyes had very similar ratings. From a design perspective, this might be considered frustrating, since the whole purpose of the design matrix was to distinguish the one final premium choice. Beyond this, the constrained schedule of the project dictated that a choice must be made. Thus, the team felt the pressure to make a decision based on some further considerations.

The first important supplemental determinant was that the Supershell design offered more flexibility. Supershell had extra volume due to using the projectile for a fuselage instead of placing the entire flyer inside of the projectile. This extra volume translated into design flexibility in light of what are probably inevitable component size changes and the addition of new components as time progresses. Also, in the unfortunate event where componentry grew beyond the shell volume (not an uncommon occurrence in the aerospace community) the engine of Supershell could be removed. Granted, Supershell is not a very efficient glider. However, the Supershell with no engine would still maintain the desired functionality through a shorter loiter time.

Another additional determinant was that Silent Eyes did not fulfill all of the initial requirements of the system. The earliest set of requirements mentioned that the system should self-destruct effectively enough so that any debris would be smaller than a can of cat food. Silent Eyes, however, had no mechanism to self-destruct the outer projectile casing, and the design afforded no room to include such an assembly. On the other hand, Supershell did have the self-destruct capability. In effect, this meant that if the team decided to choose Silent Eyes as a project, a conference with Draper would need to be arranged to readjust the requirements. This factor also favored the Supershell design.

The last contribution to the decision that was not contained in the Selection Matrix was that Supershell provided a design unique from any proposals with which the team had come in contact.¹⁷ Though the team had seen no evidence of a prototype, or even progressive design work on the Silent Eyes concept, the uniqueness couched in Supershell made it all the more engaging. Unobtainium was one of the most important goals of this project. The Supershell design provided the extra emphasis not seen in the Silent Eyes concept.

Taking these additional drivers together with the selection criteria allowed the team to be fairly confident in the selection of Supershell as the configuration for the future of the design. The design flexibility, self-destruct mechanism, and unobtainium afforded by Supershell made the final selection simple. Later, when the Selection Matrix received its final adjustments to look as it does in Figure 9, this choice was reaffirmed.

¹⁷ During the writing of this thesis, the team discovered a program working on a somewhat similar concept. The \$1.5 million project was developing some risk reduction prototypes for the Navy's Longlook proposal.

4.4 Selection Process Conclusions

As before, it is important to step back and critically review the design process at this point. The idea of creating different variants that could meet the functionality of the system was an important one. This allowed for engineering creativity to be reintroduced into the flow of the design. Also, it gave the team a chance to apply some first cut engineering approximations to see what parameters were the real drivers for the program.

The Selection Matrix was also a fundamentally sound approach to determining which one of those variants was the appropriate thrust for the rest of the project. However, in hindsight, probably more concern should have been given to the different criteria and the ultimate goal the team was trying to achieve with the final set of measures. The meeting at which the criteria were selected consisted of the student team members only. An infusion of more experienced engineering opinion would have been appropriate in this process. The final set of criteria included mostly objective values, but some wholly subjective guesses about the complexity to manufacture and operate the different systems. While subjectivity cannot be completely eradicated in the design process, the team would have been better served by making more concrete judgments when grading the different variants.

Another improvement to the Selection Matrix would be to incorporate some non-first order behavior to some of the criteria. As the matrix stands, every criterion was rated completely linearly: If the *Surveillance Area* magnitude for Supershell was twice as large as Silent Eyes, the Supershell was considered exactly twice as desirable for this criterion. Clearly, this is not necessarily the case.

With all of these limitations considered, the team is fairly confident of its choice of operations. The mission is relevant and appears to be achievable, but possibly only with expertise like that assembled at MIT and Draper Lab.

5. Communications Subsystem

One of the primary functions of WASP is the ability to transmit useful information back to the user. In fact, adding the surveillance mission to a payload with the capability of handling the projectile launch are the functions that separate this system from other similar programs that are developing. Therefore, the design of WASP has always developed with the knowledge that a communications subsystem would be necessary.

5.1 Subsystem Selection Process

The functionality of the system allowed the conceptual development of different communication processes that might answer the functional needs of the system. Several different methods were proposed, most driven by either one of the system requirements or features intended to please the customer.

The first consideration of the team was the line-of-sight (LOS) communication problem. Based on an analysis done by the team, it would be quite probable for this projectile to enter a situation where there would not be a direct LOS path from the vehicle to the ground station. Therefore, if the projectile was to be operated in a mountainous terrain or slightly over the horizon, the system needed some way to continue to transmit the surveillance information.¹⁸

Taking this problem into account, the communications group developed a trade study matrix similar to the previously discussed Selection Matrix to evaluate several different communication subsystems. The baseline case was a LOS link, each other variation was compared to the LOS case. Like with the Selection Matrix, the criteria were developed iteratively to ensure that all the possible driving factors about each subsystem was considered. Table 7 shows the different criteria and their intended meaning.

¹⁸ A study performed by team member Margarita Brito, an MIT UROP, verified the fears of the team that LOS communications were unrealistic for many scenarios.

Table 7: Communications Subsystem Selection Criteria

Criterion	Weight	Notes
Complexity	8	<ul style="list-style-type: none">• The amount of complexity associated with implementing and operating the subsystem.• This criterion would have had a higher rank if unobtainium were not such an important feature of the project.
Cost	9	<ul style="list-style-type: none">• The perceived monetary expense of the subsystem.• Cost is always a driving requirement, so the magnitude was second only to the power drawn from the system.
Technical (Schedule) Risk	6	<ul style="list-style-type: none">• The risk in the concept associated with being able to integrate all of the necessary components within the necessary time frame.
Power	10	<ul style="list-style-type: none">• The amount of power the subsystem would require.
Flexibility / Ease of Use	3	<ul style="list-style-type: none">• The ability of the subsystem to mature with future generations of the system.
Anti-jam Capability	5	<ul style="list-style-type: none">• The measure of the system's ability to resist an enemy's jamming equipment.

Using these criteria, the matrix shown in Table 8 was created. The table shows that the link through another UAV or similar system seems to be the most attractive system at this time. It should be noted that this matrix is still very fluid, and that a final design choice has not yet been made. Conceptually, all of the designs besides LOS are the same; each design merely has its own unique way of transferring the messages between the ground station and the projectile.

Table 8: Communication System Trade Study

	Rating Parameter	Complexity	Cost Risk	Technical (Schedule) Risk	Power	Flexibility / Ease of Use	Anti-jam Capability
LOS	Parameter Weight	6	9	6	10	3	5
	Raw Score	3	10	9	10	1	3
	Weighted Score	18	90	54	100	3	15
Balloon at Ground Station	Raw Score	2	7	8	10	8	5
	Weighted Score	12	63	48	100	24	25
							272
Balloon in Projectile	Raw Score	10	1	2	1	8	5
	Weighted Score	60	9	12	10	24	25
							140
Repeater Projectile	Raw Score	5	2	7	7	10	5
	Weighted Score	30	18	42	70	30	25
							215
Satellite Link	Raw Score	7	6	5	3	10	3
	Weighted Score	42	54	30	30	30	15
							201
Other UAV or AWACS	Raw Score	5	10	9	10	8	5
	Weighted Score	30	90	54	100	24	25
							323

5.2 Link Budget

A fundamental element of communication system design is the link budget. The link budget tracks the signal from its originating source to the final reception of the signal at the receiving station. From a design perspective, a link budget allows for a theoretical development of different system schemes to determine which best meets the requirements of the subsystem.

5.2.1 On the Vehicle

The link begins at the transmitter. Each antenna is characterized by a gain pattern; the high-g environment drove the team to select a rugged microstrip patch antenna with a typical gain G_t given by:

$$G_t = 4 \text{ dB} \quad (1)$$

There is another effect on the link at the transmitter. There is a loss associated with the antenna feed to the transmitter. In general, this line loss, L_t , varies from 1 to 3 dB.¹⁹ For this system, the feed loss is assumed to be:

$$L_t = 1 \text{ dB} \quad (2)$$

A common measure for a communications system is the Effective Isotropic Radiated Power (EIRP), usually measured in dB. By definition, *EIRP* is the total power that would be needed if the transmitter were to radiate the same level of RF illumination in all directions.²⁰ Quantitatively, the *EIRP* is the power output from the transmitter multiplied by the gain of the transmitter and divided by the feed loss. The decibel equation is then:

$$EIRP = 10 \log P + G_t - L_t \quad (3)$$

¹⁹ Space Mission Analysis and Design. Larson and Wertz, ed. p. 536.

²⁰ Gordon, Gary D., and Walter L. Morgan. Principles of Communications Satellites. John Wiley & Sons, Inc.: New York, 1993. p. 167.

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Note that the *EIRP* is a function only of factors associated with the transmitter. Furthermore, for a given antenna and internal configuration of the transmitter, *EIRP* is a function of the output power, P .

5.2.2 Vehicle to Link

The next piece of the link is the propagation of the wave between the transmitting antenna and receiving antenna. There is a loss due to the distance between the antenna referred to as the space loss. One way to look at the space loss is that the power found from the *EIRP* must be distributed evenly across the surface of a sphere. The space loss looks like the surface area of a sphere.

$$L_s = \left(\frac{4\pi S}{\lambda} \right)^2 \quad (4a)$$

or

$$L_s = \left(\frac{4\pi S f}{c} \right)^2 \quad (4b)$$

or in decibel form,

$$\begin{aligned} L_s &= 20 \left(\log S + \log f + \log \left[\frac{4\pi}{c} \right] \right) \\ &= 20 (\log S + \log f) - 147.55 \end{aligned} \quad (4c)$$

where S is in meters and f in Hz.

5.2.3 At the Receiver

The final piece of the link is the receiver contribution. Every receiver intercepts a certain amount of noise from the environment that it is searching for a signal. This noise is characterized by a noise temperature which lumps antenna noise, receiver noise, and all other noise into a single parameter called the system noise temperature, T_s . According to Gordon and Morgan, the noise temperature is around 290 K.²¹

The gain of the receiver antenna, G , is primarily based on its diameter of the antenna, and is generally fixed for a given system. Thus, a figure of merit, symbolically termed G/T_s , is used to describe the overall quality of reception at the receiving station. For satellites, these

²¹ Ibid., p. 40.

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²¹ Ibid., p. 40.

figures of merit range from -20 to 10 dBi/K.²² The decibel equation for the figure of merit when the gain of the receiver is given in dB is then,

$$G / T_s = G_r - 10 \log T_s \quad (5)$$

To get an idea of how well the communications link works, then, the next step is to look at the ratio of the carrier power to the thermal noise encountered at the receiver. This value is just the original *EIRP* multiplied by the receiver figure of merit and divided by the space loss, or, in dB,

$$C / T_s = EIRP - L_s + G / T_s \quad (6)$$

The last factor to be discussed is the noise generated at the receiver input. This noise power can be modeled with a uniform power spectral density called N_o , which is related to the system temperature T_s by Boltzmann's constant ($k = 1.3806 \times 10^{-23}$).

$$N_o = kT_s \text{ W / Hz} \quad (7)$$

Now, dividing (6) by k (or subtracting in dB) results in the carrier-power-to-noise-density ratio. This value is important, because it tells the energy that the signal has at the receiver relative to the system noise floor. In dB, the equation follows from (6).

$$\begin{aligned} C / N_o &= EIRP - L_s + G / T_s - 10 \log k \\ &= EIRP - L_s + G / T_s + 228.6 \end{aligned} \quad (8)$$

Dividing the total energy in (8) by the data rate, R , yields the bit-energy-to-noise ratio

$$E_b / N_o = EIRP - L_s + G / T_s - 10 \log R + 228.6 \quad (9)$$

Every modulation scheme has a relationship between the bit energy-to-noise-density ratio and the desired level of transmission accuracy. That is, for a given modulation and coding scheme, the bit-energy-to-noise-density needed to provide the given level of performance is

known and is usually give in terms of bit error rate. The last step is to compare this required E_b/N_o to the amount of energy found from (9). This difference is called the link margin.

$$M = E_b / N_o - (E_b / N_o)_{req} \quad (10)$$

However, by prescribing a common modulation and coding scheme and a margin, (3), (4c), (9) and (10) can be combined to determine the relationship between the data rate and the power required.

$$10 \log R = 10 \log P + G_t - L_t - L_s + G/T_s - M - (E_b / N_o)_{req} + 228.6 \quad (11)$$

5.3 Possible Wide Area Surveillance Projectile (WASP) Links

During the development of the communications subsystem, the team knew that power would be a severe constraint. From the first cut approximations developed at the time of the variant selection, one of the tightest constraints each subgroup faced was fitting batteries into the allotted volume. For this reason, the communications subgroup wanted to determine the amount of power that would be required to handle the data rates required for the mission. With certain assumptions, the equations found in Section 5.2 allowed the team to consider how some of the schemes proposed in Table 10 would perform the mission.

Since the systems design of the projectile was occurring in parallel with the communications subsystem design, the subgroup knew that the final configuration would likely not be Twin Shells--the only design to accommodate the LOS problem. Therefore, the links would all have to be through an intermediate point. How to accomplish that pivotal communication point could then be considered the design problem for the communications subgroup.

In order to gain insight into different possible approaches, four scenarios were explored to determine the power needed for the communication system. The four links were from the projectile to:

- a geosynchronous communications satellite;
- a middle earth orbit military satellite;
- a low earth orbiting cellular phone satellite; and,
- another UAV, AWACS, or repeater projectile.

Each of these scenarios contained different assumptions that would affect their link performance. For the GEO communications satellite, the distance from the projectile to the satellite would be approximately 35,000 km. Also, IntelSat communication satellites all have one K_u band receiver on board²³, so a frequency of 12 GHz was assumed. (For readers unfamiliar with communications terminology, Table 9 has been included to show a list of the common radio frequency bands.) The figure of merit for IntelSat ranges from -12 to +2, so a conservative value of -8.5 was chosen for this evaluation.

Table 9: Letter Designators for Frequencies

<i>Approx. Frequency Range (GHz)</i>	<i>Letter</i>	<i>Typical Usage</i>
1.5-1.6	L	Mobile-satellite service (MSS)
2.0-2.7	S	Broadcasting-satellite service (BSS)
3.7-7.25	C	Fixed-satellite service (FSS)
7.25-8.4	X	Government satellites
10.7-18	K_u	FSS
18-31	K_a	FSS
44	Q	Government satellites

The military satellite scenario was based on the probability that the primary user of the system would probably be the US military. There are presumably some intelligence satellites orbiting the earth that could be used by WASP for this mission, so it was assumed that the satellites altitude was approximately 15,000 km. According to a Draper contact, the Predator

²³ Gordon and Morgan.

and Outrider UAVs communicate to satellites over the K_u band, so the same 12 GHz frequency was chosen for the scenario. Based on what everyone *thinks* the National Reconnaissance Office (NRO) spends on these intelligence satellites, it is safe to assume that the systems operate state-of-the-art equipment and that the receivers have a G/T_s of at least 5.

The LEO approximation is fixed on the new global telecommunications satellite constellations that will soon be circling our globe. Motorola's Iridium will communicate on the L band and will orbit at around 1000 km. A good but achievable G/T_s of 3 was assumed for the platform.

The last concept tested called for using either another projectile as a repeater station, another UAV in the theater to relay transmissions, or an AWACS type system receiving data. In any case, the maximum foreseeable distance from the projectile was predicted to be 400 km. Based on the same Draper contact quoted above, the Predator and Outrider UAVs communicate in-theater in the C band, so a frequency of 4 GHz was used in the calculations. A fairly aggressive G/T_s of 5 completed the criteria for this scenario. To see these scenarios in tabular form, see Table 10.

Table 10: Possible Communications Links

	Mission	S km	F GHz	G/T_s dB
1	GEO Comm Sat	35,000	12	-8.5
2	MEO	16,000	12	5
3	LEO Cellular Sat	1,000	1.55	3
4	Other UAV	400	4	5

In the calculations, there were a couple of assumptions made for all of the designs. The first was that the gain of the transmitting antenna was 4 dB. This figure is typical of a patch antenna, which is the kind of antenna used on a high-g projectile communication system being developed at Draper.

Another assumption was that the line loss in the transmitter was 1 dB. Also, a margin of only 1 dB was employed. Finally, the required E_b/N_o used for the calculation was 4.4 dB. Again, this value is somewhat aggressive, but should be able to be achieved with the right coding scheme.

Considering Eqn 11 from Section 5.3 for these scenarios, the plot shown in Figure 10 was made that shows the possible data rate over a range of powers.

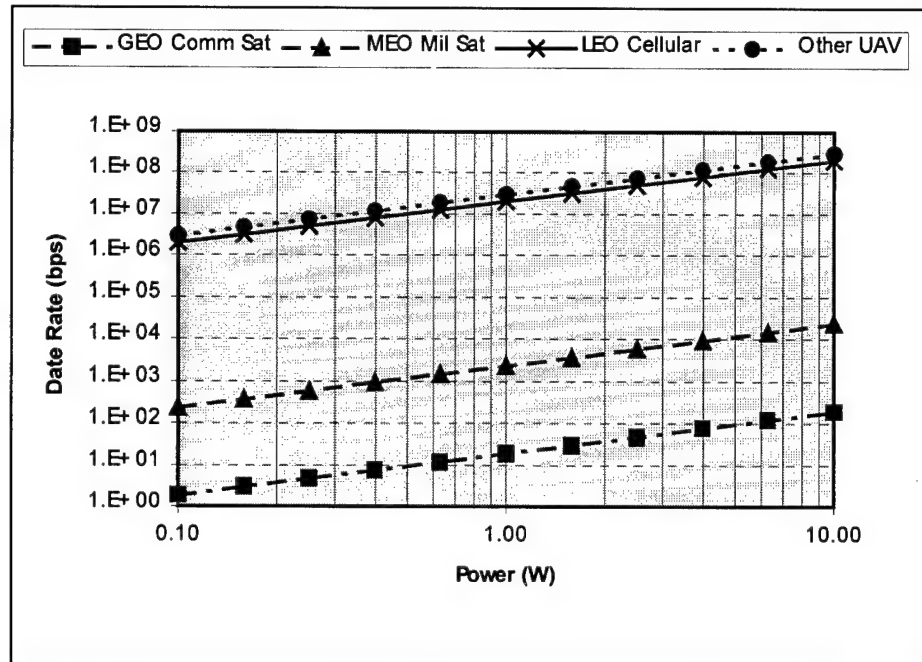


Figure 10: Data Rate vs. Power Required

Figure 10 is not very useful, though, until a feel for the data throughput is determined. For this type of system, a standard 800x400 pixel CCD is assumed. If the imager uses an 8 bit gray scale for each pixel and the image processor can compress the images to 1/50th the original size²⁴, the data throughput will be approximately 50k bps. Referring back to Figure 10, then, the higher two choices--the cellular link and the other UAV--provide an adequate link. The others, the GEO communications satellite and the MEO military satellite, do not provide the necessary bit rate.

5.4 Combined Global Positioning System (GPS) and Receiver Subsystem

One of the more exciting features of the communications subsystem is that it afforded some room for invention. In order to understand this statement, the reader must know something about the communication systems on this type of vehicle.

²⁴ Team member Vlad Gavrillets investigated this problem and found many compression algorithms that could compress the image data this much and even more.

In this industry, there are no OTS components that can withstand the extreme accelerations produced inside a projectile. Rather, a new component must be built from designs that have survived the high-g loads in the past. Because there must be so much customization, the step from this conventional approach to having a whole new type of transmitter or receiver is not as risky a proposal as it is in some other areas of the design.

This said, the communications subgroup wanted to further the design of the subsystem with as much optimization as possible. It seemed evident that one of the largest constraints on the system would be power, therefore the communications design might be developed in such a way as to minimize the power drawn.

One place where there seemed to be some overlap of existing functionality was between the onboard GPS receiver, used for navigation, and the uplink receiver used for command of the vehicle. Both messages are relatively low bandwidth, and having separate antennas on-board for all three communicating functions--downlink transmitter, uplink receiver, and GPS receiver--seemed redundant and too inefficient for the WASP design.

The team proposes instead to use the GPS frequency to uplink commands, and to use the same antenna and radio frequency (RF) front end as for the GPS signal. The final GPS/RX system would use much less power than if each subsystem were implemented separately.

5.4.1 GPS Fundamentals

In order to better understand the concept, some knowledge about the GPS system is necessary. The GPS satellite system consists of 24 satellites in six orbital planes. Each satellite produces a signal that includes data describing the orbital parameters of the satellite at a specific time. A GPS based navigation system can determine the times at which signals arrive from the different satellites and thus determine its own position. Signals from four satellites are required to determine time and the three coordinates of position.

The different GPS signals are all tracked on one of two frequencies: either L_1 (1575.42 MHz) or L_2 (1227.6 MHz). Each satellite produces a signal cloaked in a unique pseudo-random code which allows a GPS receiver to interpret the code. The code is called pseudo-random because it is a well-defined sequence, but a receiver not programmed to interpret GPS code would see the signal as noise.

Typical GPS receivers have the GPS codes loaded into memory. By comparing the received signal with the stored code, the receiver can determine which satellite has sent the

message and decode the information produced by that satellite. In order to deal with more than one satellite simultaneously, the GPS receiver has a set of channels--each of which compares the code of a specific satellite to the incoming signal. Figure 11 shows a common architecture for a GPS system; the shaded area in the figure shows the functions which are performed by each channel.

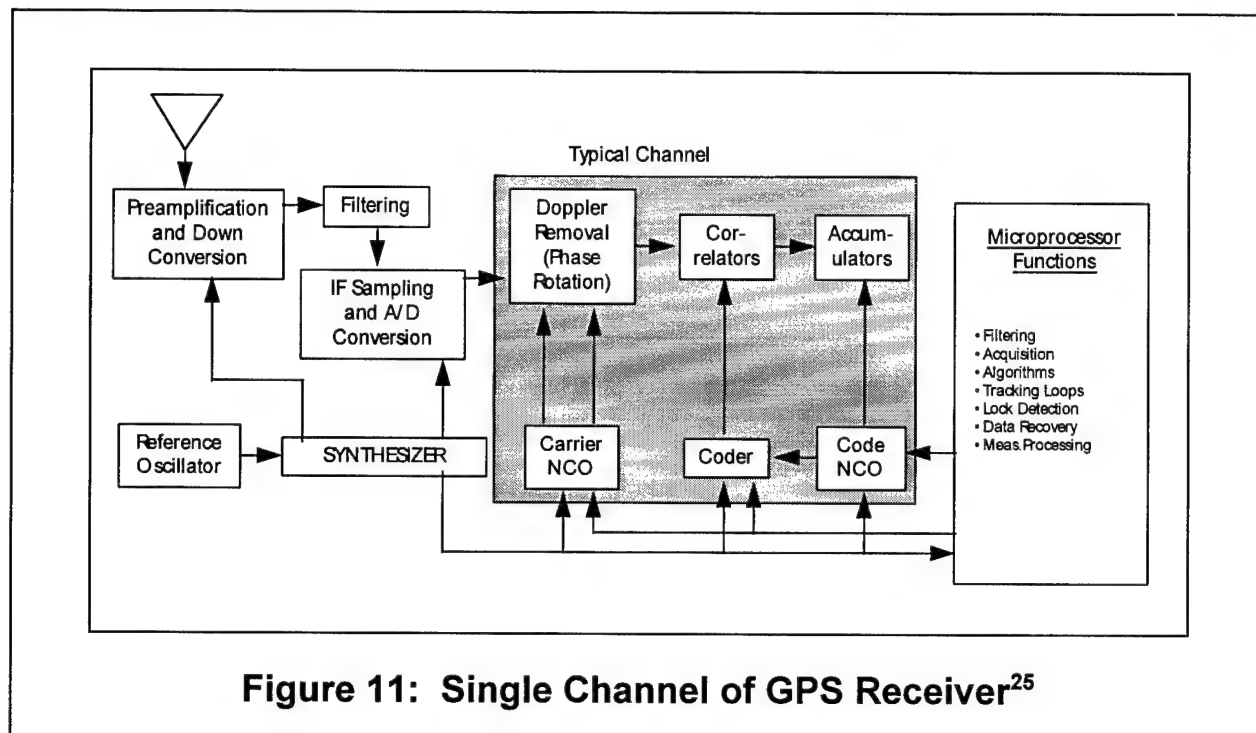


Figure 11: Single Channel of GPS Receiver²⁵

For example, suppose the GPS receiver has twelve channels on board to track satellites--a typical modern system. Most of the 24 satellites in the constellation would not be within the view of that receiver, certainly less than twelve. Therefore, the receiver is trying to match the code of many more satellites that are physically possible to see. This feature of the system must necessarily be recognized in order to make the argument that one can allocate one of the channels to the uplink communications system.

It is also important to note that each channel is not hard coded to a specific satellite. Rather, as the processor updates its position and needs to move to new satellites, the processor downloads the pseudo-random code of new satellites into the channels and begins the correlation process with respect to the new expected signal. If each channel were hard wired

²⁵ Modified from *Global Positioning System: Theory and Applications*. Bradford Parkinson and James J. Spiker, Jr., ed. p. 338.

for certain satellites, it would be a much more difficult task to reconfigure the system to operate with fewer than expected satellite channels.

5.4.2 System Concept

The preceding fundamentals allow a more in-depth discussion of the proposed concept. Essentially, the team intends to convert one of the GPS channels into a channel dedicated to a communications uplink. The ground station transmitter would output a signal that is very similar to the present GPS satellite transmission. However, instead of using one of the present GPS signals, the communications signal would be carried by its own orthogonal pseudo-random noise signal.

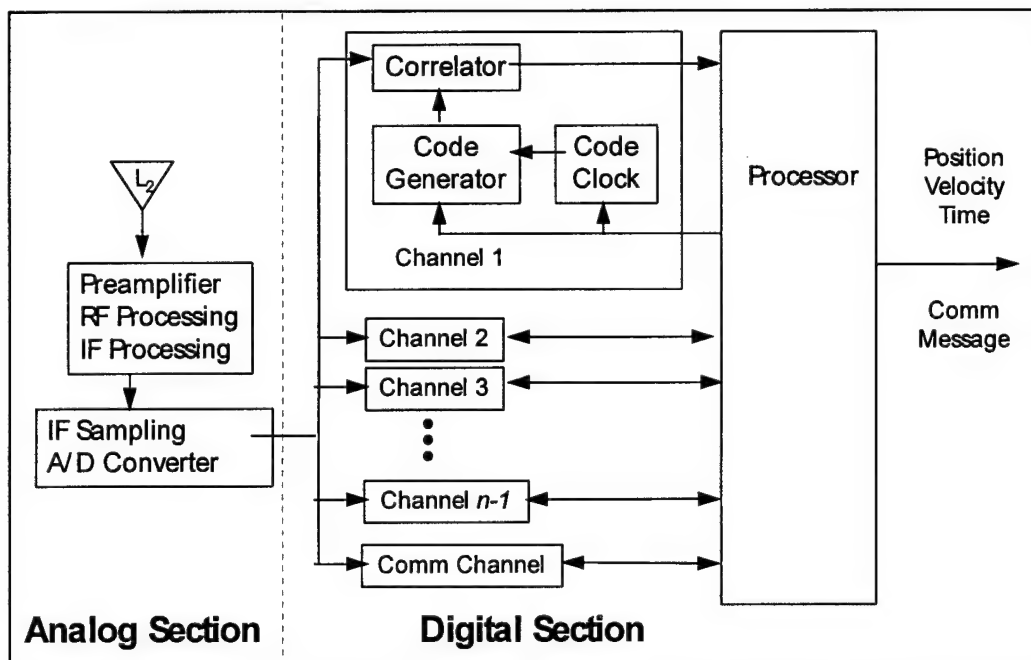


Figure 12: Proposed Communications Link

After receiving this signal, the receiver processor could process the signal much in the way that the other GPS signals are processed but using the unique code for the communications function. More specifically, looking at Figure 11, every piece of hardware on the diagram would remain the same as in past designs. The added capability could be built into the system by merely modifying the software.

Understandably, the phrase '*merely modifying the software*' must be viewed skeptically. In fact, the development of new software would be the main difficulty of the project and a challenging effort for the WASP team of engineers. Typically, these GPS processors are controlled by large embedded programs--on the order of 75,000 lines of code.²⁶ Programs of such a size are difficult to develop and test.

Beyond the magnitude of the task, there are proprietary issues associated with modifying GPS processing algorithms. GPS receiver manufacturers have spent a lot of time and money on the development of their navigation algorithms and would have to be persuaded that it is in their best interest to allow a the WASP team access to their source code. It may be more efficient to specify the required changes and contract with the manufacturer to deliver a receiver with the specified functionality.

However, the team feels that such issues are negotiable. There is a large market of GPS manufacturers, each of which would like to give its product line a competitive edge.²⁷ The interesting capability that would be provided for a joint GPS and communication system might be intriguing enough to solicit participation in the project by a manufacturer. Unquestionably, a team of computer scientists already familiar with the code working in a GPS processor could readily make the modifications necessary to provide this communications capability. Functionally, the major change needed in the processor is the ability to process the bit stream as a communications stream.

To sum up the conclusions of the team, the combined GPS and Receiver subsystem is an idea worth pursuing. There will be difficulties and risks, but that is what this project is supposed to pursue vigorously. By bringing a GPS manufacturer into the design, a new system could be built and tested in a relatively short period of time.

²⁶ Interview with Joseph Przejmski, Draper Labs.

²⁷ In *Understanding GPS*, published in 1996, Kaplan lists 47 manufacturers world-wide..

5.4.3 Potential Growth for the Concept

Another exciting aspect of the combined GPS/RX subsystem is that there are a number of ways the initial concept could expand its functionality if the concept proved viable. The most obvious quick upgrade to the concept would be to add extra channels for the processor to operate. GEC Plessey Semiconductors sells a system that tracks seven channels with an Intel 80186 as the system processor. The same system is compatible with an Intel 486. This system could probably be upgraded to more fully stretch the more capable processor's faculties, or use an even more modern processor with greater performance capacity. By appending an arbitrary number of channels, the GPS receiver would not have to sacrifice any of the channels already on board.²⁸

This concept, using a seven channel processor, does have some drawbacks. For instance, every new generation of processor usually requires more power. Therefore, a tradeoff would have to be investigated between the added power consumption of a new processor versus the new capability it would provide. Another shortcoming of the growth potential is that new hardware would need to be added to the current receiver designs. For every new channel, each of the components within the gray shaded area of Figure 11 would have to be replicated. Conceptually, such a design change is straightforward, but the extra space and power required by the new components might make this extra capability too costly. Finally, this design assumes a fairly capable ground station. That is, the ground station must emulate how ever many satellites the new processor can handle.

The disadvantages of the previous system lead to another variant of the concept. Instead of adding new hardware, more of the already present channels could be allocated to the communications task. In this case, no new power or hardware would have to be built into the design. The ground station would still have to be able to produce more than one GPS signal, but the number of satellites it would have to emulate would be limited to the number of channels already on board--usually twelve.

One final way to increase the capability of the concept will be developed more fully in the following section, but bears mention at this time for the sake of completeness. More data can be sent in one signal if the power behind that signal is increased (see Section 5.2 Link Budget). Therefore, by increasing the uplink power, a much higher data rate can be achieved

on the same channel than if the transmitter used the same power level as a satellite produces. This variant would have the same hardware as past designs, but the software upgrade would be more involved. Namely, the processor would then have to be configured to handle different final data rates from the GPS signals and the data link.

These kinds of growth possibilities make the combined GPS/RX concept promising. By working with a manufacturer of a receiver product, the an important technology could be developed that would enhance the performance of the design.

5.4.4 Jamming Problem

One of the most evident problems with all GPS systems is the inherent jamming probability that comes with having a well-known frequency of operation for the system. Essentially, this allows the jammer to concentrate the power of the jamming signal at that frequency. The way the GPS signal defends against this is by using a coding scheme which results in significant signal-to-jammer gain when the signal is processed inside the receiver.

Jamming becomes an issue for the GPS/RX system, because adding another transmission on the same GPS frequency creates more potential for jamming. As mentioned in the previous section, adding more power to the transmission will enable the system to transmit more bits per second on the same frequency. It will be shown that if the power at the transmitter is on the order of what the GPS satellites produce, the GPS receiver will have no problem handling the signal. The problem then becomes how much power the uplink can use without jamming the GPS receiver.

As discussed in Section 5.2 Link Budget, every receiver has a system temperature or noise level that varies with the temperature of the receiver with Boltzmann's constant. This parameter is known as the noise floor of a receiver. For this GPS/RX concept, as long as the uplink transmitter outputs a signal whose received power is below this noise floor, the signal will not interfere with the GPS/RX any more than the rest of the noise the receiver must process.

²⁸ This could be an issue for a team trying to incorporate as many signals as possible from GPS and GLONASS satellites as well as from other guidance sources.

Assuming the receiver operates at room temperature, the noise floor for the system is compared with the theoretical noise floor given by:

$$\begin{aligned} N_o &= kT_s = 1.38 \times 10^{-23} \text{ J/K} \cdot 290\text{K} \\ &= -204 \text{ dBw/Hz} \end{aligned} \quad (12)$$

The receiver is also rated by the amount of noise it adds to the signal by the internal receiver components. This value is called the noise figure, NF .^{29,30} A conservative assumption for GPS receivers might be 4 dB³¹, which is added to the theoretical noise floor. Therefore, the noise created by the external environment and the internal components is -200 dBw/Hz.

One of the advantages of the GPS system is that it broadcasts its signal within a relatively wide bandwidth, occupying 10 MHz on either side of the center frequency. The GPS signal is thus spread over approximately 20 MHz. Therefore, the amount of noise power in this 20 MHz band is just a simple multiplication between that found in (12) and 20 MHz. In dB, the equation is then a sum (and 20 MHz = 73 dB-Hz).

$$\begin{aligned} N_{tot} &= N_o + B = -200 + 73 \\ &= -127 \text{ dBw} \end{aligned} \quad (13)$$

This, then, is the total receiver noise power. To find the signal-to-noise ratio, some common knowledge about the GPS system can be employed. It turns out that GPS satellites were designed to produce a minimum power level at the receiver. Table 11 shows the different minimum power levels for each operating frequency and code

²⁹ Bird, Jonathon. "An Introduction to Noise Figure." RF Design. March 1993, p. 78-83.

³⁰ Biller, Robert P. "Understanding Receiving System Design Parameters." Microwave Journal. February 1985, p. 175-177.

³¹ Understanding GPS, p. 218.

Table 11: GPS Minimum Power Signals³²

Frequency	Code ³³	Minimum Signal Power (dBw)
L ₁	C/A	-159.6
L ₁	P(Y)	-162.6
L ₂	P(Y)	-165.2

In dB form, the SNR is quickly found. The only assumption needed is a signal power from Table 11, the most conservative value being for C/A code on L₁.

$$\begin{aligned} SNR = S - N_o &= -160 - (-127) \\ &= -33 \text{ dBw} \end{aligned} \quad (14)$$

(14) reveals two interesting features. First, the signal power at a GPS receiver is much weaker than the noise seen by the receiver. Secondly, it can be inferred that the GPS processing gain must add 37.4 dB of signal gain to achieve the 4.4 dB signal-to-noise ratio previously discussed. An addition signal gain of 3 dB will allow an uplink received power level equal to the receiver noise level without adversely affecting GPS performance.

The last item to consider is the bit energy per noise ratio achieved by transmitting an uplink at this level. Using the fact that the GPS data rate is actually only 50 bits per second (bps), the bit energy to noise ratio can be determined.

$$\begin{aligned} E_b / N_{tot} &= S - N_{tot} - R = -160 - (-200) - 17 \\ &= 23 \text{ dB} \end{aligned} \quad (15)$$

³² Taken from Table 4.4 in *Understanding GPS: Principles and Applications*, ed. Elliot D. Kaplan. Artech House, Boston: p. 97.

³³ C/A code stands for Coarse/Acquisition or Clear/Acquisition code and is the most commonly used GPS code, available to civilian and military users. P(Y) code is the Precision or Protected code, a more complex code which can be encrypted (when it becomes the Y code) during times of war.

Therefore, the typical GPS system has an E_b/N_o of 23 dB for 50 bps. For the communications link, though, without margin the E_b/N_o only has to be 4.4 dB. Thus, there is an excess of $23 - 4.4 = 18.6$ dB of E_b/N_o . If the communications system uses all of this excess to increase the data rate, a new and increased data rate could be achieved.

$$\begin{aligned} R &= 50 \cdot \text{Excess} = 10 \log 50 + 18.6 = 17.0 + 18.6 \\ &= 35.6 \text{ dB - bps} = 3.63 \text{ kbps} \end{aligned} \tag{16}$$

This uplink capability far exceeds what is expected by the team. In fact, the 50 bps rate used by the GPS signal would probably be quite enough bandwidth. However, this result in (16) shows the additional capacity of the system.

5.5 Ground Station

One piece of the system architecture which has, to this point, been little discussed is the ground station. For the most part, the assumption of the team was that the ground station would be developed from mostly off the shelf hardware using tailor-made software. Through the design process, this conceptual view of the subsystem has remained the same.

During a discussion with the Defense Advanced Research Organization (DARO), the team learned of a Department of Defense (DoD) program that is supposed to provide a framework for the ground stations of defense UAVs, present and future. Though this program, called Tactical Control System (TCS), is still developing, it has designed a set of expectations and design requirements that future UAV ground stations will be expected to meet, according to Ken Sola, military liaison for TCS.³⁴ Because this directly relates to the future of the project and future UAV communication systems, this thesis will use the TCS as a case study for the ground station for WASP.

The UAV Joint Program Office (UAV JPO) describes the system roughly as follows: *The TCS will control multiple types of UAVs and payloads, each with unique performance characteristics. Additionally, the TCS is to relay information to Command, Control, Communications, Computers, and Intelligence (C4I) units specific to the controlling service. Isolated and portable software control modules for unique UAVs will allow for integration of various air vehicle and payload manufacturers' unique components within the common operating environment. The service will define the desired level*

³⁴ Telephone interview with Ken Sola.

of TCS functionality, the battlefield connectivity, and the air vehicles and payloads to be used depending upon the deployment concept and area of operations. This provides for scaleable hardware configurations tailored to support the user's needs. Finally, TCS will provide a common human-computer interface for tactical airborne platforms to simplify user training and provide seamless integration into the services existing C4I systems³⁵

The prime directive of TCS is evident from the first word in its name: Tactical. To date, most of the UAV and other intelligence gathering instruments are commanded at the division or brigade level³⁶, sometimes higher. However, as UAVs become smaller, cheaper, and more autonomous, their command level shrinks accordingly. The TCS, then, describes how to make a ground station that is capable of being supported by a company level unit or smaller.

There are five different levels of support in the TCS scheme as shown in Table 12. Each incremental level portrays another level of control by the ground station. The argument for placing autonomy control in the ground station is that it allows the expensive and sometimes cumbersome decision-making hardware to be placed in the more benign environment of behind friendly lines. Also, cost can be reduced since one ground station can control several different UAVs, thereby decreasing the number of ground stations that would be required.

Table 12: TCS Levels of Autonomy

Level	Description
I	• Secondary Product
II	• Direct Data Receipt
III	• Payload Control • Direct Data Receipt
IV	• Flight Control • Payload Control • Direct Data Receipt
V	• Launch and Recovery • Flight Control • Payload Control • Direct Data Receipt

³⁵ Paraphrased from the 11 October 1996 DRAFT of the Tactical Control System (TCS) Data Dictionary, prepared by the Dahlgren Division of the Naval Surface Warfare Center.

³⁶ For the purposes of this paper, the term company refers to a group of approximately 100 troops all with primarily the same mission—whether that be light infantry, artillery, or transportation. A brigade would be composed of approximately three companies, and a division of three brigades or more.

Appendices

<i>Appendix</i>	<i>Title</i>
A	Quality Function Deployment (QFD) Requirements Matrix
B	Functional Flow Diagram (FFD)
C	Requirements Document

Appendix A: Quality Function Deployment (QFD) Requirements Matrix

Appendix B: Functional Flow Diagram (FFD)

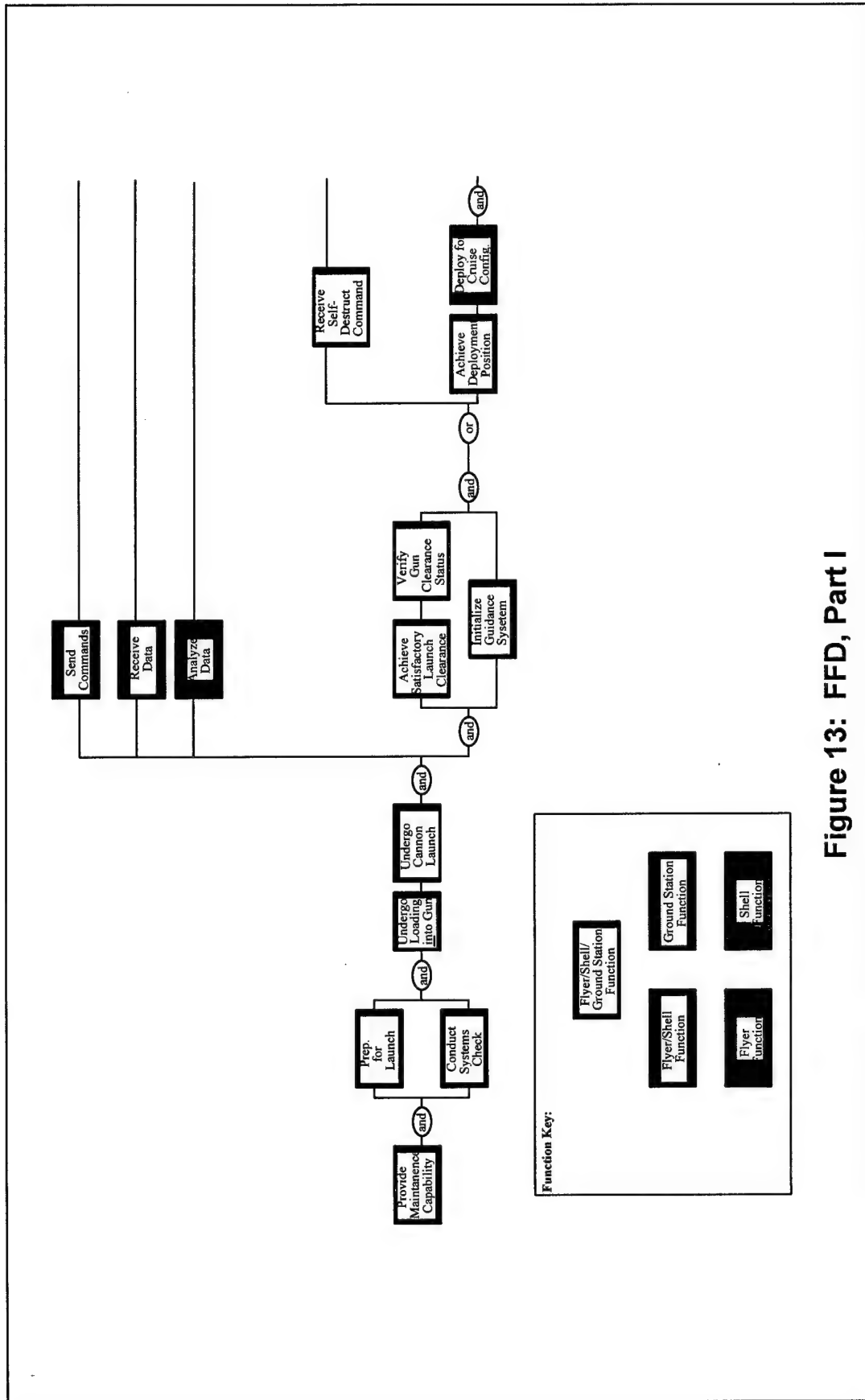


Figure 13: FFD, Part I

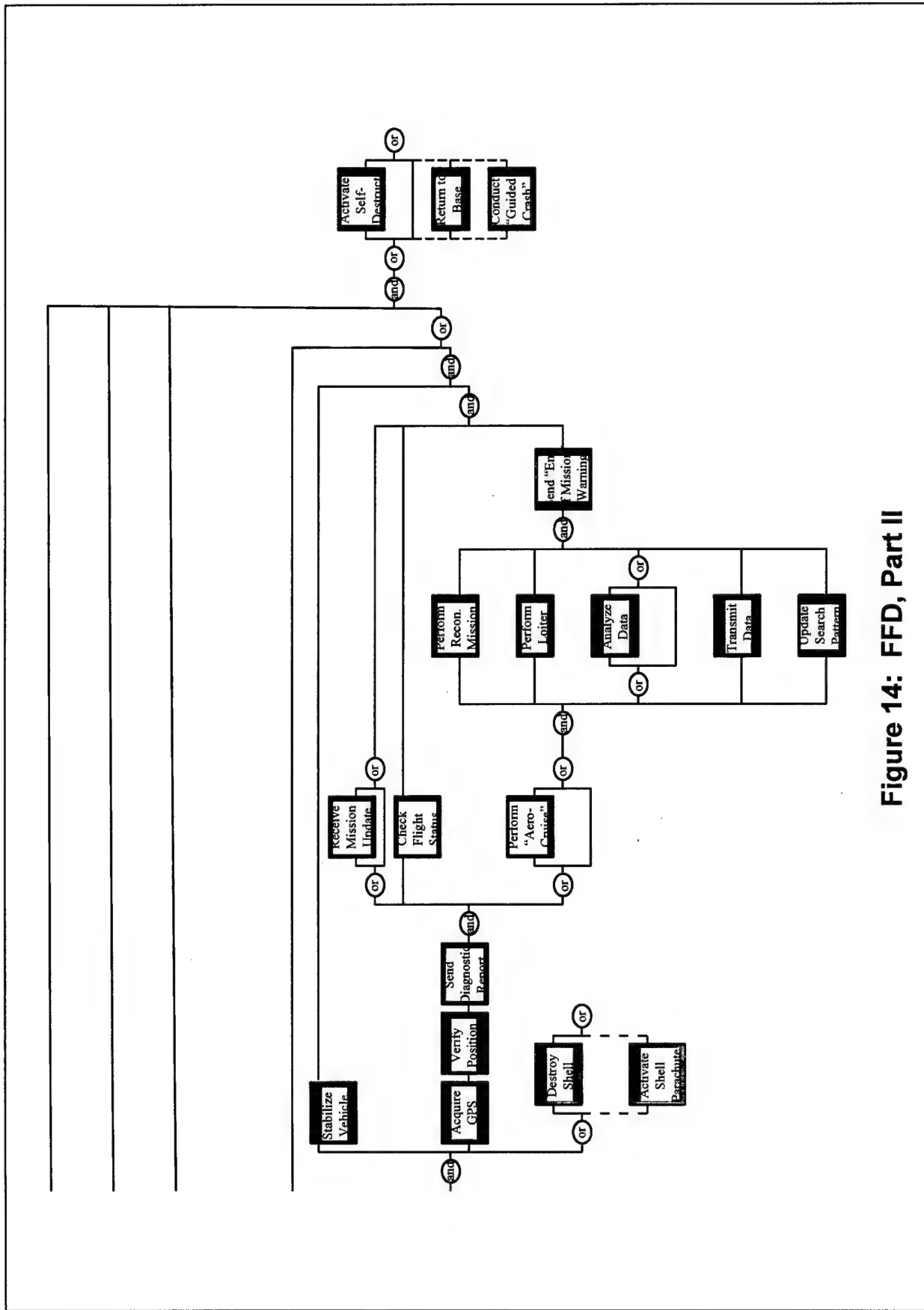


Figure 14: FFD, Part II

Appendix C: Requirements Document

MIT/Draper Technology Development Partnership

Low-cost Instrumented Surveillance Projectile (LISP)

System Requirements

(Status: 2 January 1997)

o General System Functional Goals:

The non-lethal LISP system goal is to provide local theater commanders with rapid localized reconnaissance information that can be used in a timely manner as an aide to ensure mission objectives are secured. Launched from the sea or from land (see operational scenario), 5-inch or 155mm projectile launchers will be the basic interface for LISP operations. Ideally, LISP's surveillance objectives should be selectable just before launch, while LISP is en route, and during the system's flight data collection and/or targeting mode. Since LISP's are expendable - low cost will be an important design driver. While the primary functional objective is surveillance, LISP's secondary goal is to provide a temporary network of airborne relay stations that can be used for linked line-of-sight communications.

o Range:

70-200 miles from launcher using rocket-assisted projectiles.

o Time aloft after projectile delivery / operating time:

1 to 8-hours and this will depend to some extent on trades made between system performance, complexity, and cost. Operational time: 2-hours.

o Desired surveillance area:

To be determined as the typical "Area of Action" or operational area for a self-sustained Marine Brigade.

o Projectile diameter / length:

5-inch or 155mm diameters. Length will be consistent with existing projectiles in this class.

o Location accuracy:

Several meters.

o Sensor type:

Primary focus should be on an imaging camera.

o Self destruct mechanism:

Self destruct will ensure that no piece of the destroyed projectile will exceed the characteristics of an 8-oz can of cat food. For military operations - the flyer will also be designed to self destruct at the end of its useful mission.

-
- o Acquisition cost target:
Conventional 5-inch and 155mm munitions cost approximately \$800. Rocket-assisted projectiles in this class can cost \$10,000. The expendable LISP (projectile, flyer, and sensor package) cost should be within the \$20,000-\$30,000 range in production.
 - o Information timing:
Near-real-time.
 - o Level of autonomy:
To be determined via system trades.
 - o Existing physical, political, or organizational constraints:
LISP must be inexpensive to ensure its use in local theater operations.... organic. Projectiles in this class spin at 250 Hz - so a slip obturator (launch shroud) of some type might be required to ensure "near-0" launch spin for LISP
 - o Environment:
Launch "g"s baseline - 10,000. However, "g"s will increase if trades suggest that the LISP system will result in an integrated projectile with weight less than that of conventional munitions.
 - o Shelf life:
Approximately 20-years with provisions for replacing batteries and expendables for flyer and communications at pre-determined intervals.
 - o Existing surveillance MOEs:
Not aware of any at this time. Check with potential customers once design project is underway.
 - o Covertiness level:
The flyer sensor package is expected to be quite small. So an effort should be made to ensure that large flyer components like wings or rotating components like propellers and rotors are of suitable materials to ensure that low RADAR signatures are maintained. Visual and acoustic signatures must also be low.
 - o Reliability expectations:
90% availability. That is to say - one out of 10 LISPs might not perform as expected.
 - o Extensibility:
The primary extension of the LISP concept is to provide a temporary LOS communication network for relaying data and messages. Additional sensor applications, beyond static imaging, for all-weather operations (RADAR?) and chemical/biological sampling should be considered. Acoustic, IR, and motion sensors are also of interest. LISP variants should be adaptable to address civil and commercial needs providing that the system can be adapted to smaller launchers and possibly smaller projectile sizes.
 - o Prep. and launch time:
2 to 3-minutes

o Safety issues:

LISP will be stored in magazines along with conventional munitions. As such, it will have the same or better characteristics as munitions when exposed to mishandling, fire, or detonations.

o Special demonstration considerations:

LISP will be field tested at the Navy's Test Facility in Dahlgren, Virginia. For the field test, a 70+ mile range will not be required. In addition, it would be desirable to retrieve the test article and as such - no self-destruct mechanism will be assessed during the planned system demonstration period.

Some additional information

o Picatinny Arsenal has tested a \$5000 hockey-puck sized imaging camera that can withstand 21,000 "g"s. This Xyberion system includes a 50-mb data transmitter and base station for receiving the image.

o Draper's Judy Miller can provide UAV scenario trajectories for our use. In addition, Don Gustavson has the ability to simulate any projectile trajectory.

o Draper's Jack Stevie and Bob Polutchko have information on Draper's Parafoil designs.

o Draper's Dick Phillips has background information on triangulating to obtain range using GPS during a position fly-by.

o There is data available for a very small Wankel Engine that might have application to LISP.

o Draper's Paul Motyka and John Dowdle have information on gun barrel environments.

Abstract

The aerospace industry began as a market in which manufacturers for the most part had a known paying customer for their product. Even today, Boeing has aircraft buyers waiting in line for new 737 and 777 models. The industry has not fully developed, and the need of improved technology is still very present. However, as the industry matures this luxury is quickly eroding. Like most other industries, aerospace manufacturers in the future will have to independently determine some need that is present and they could fulfill, develop a product to meet that need, and then market their finished product. This can be a daunting process when considered in light of the million and billion dollar cost of most research and development programs in the aerospace industry.

Determining future national aerospace needs is a long and difficult process. Working as a project team, the MIT/Draper Technology Development Project had a challenging opportunity to project a future national aerospace need which could be best met by a group from MIT and Draper. This thesis documents the developmental process of an intelligent projectile from need determination through the preliminary design phase.

After a deliberate and thorough search, the team settled on a innovative aeronautical vehicle which could withstand a high-g launch then retrieve and transmit data to a remote ground station. Based on this fundamental premise, the team then began the design process to develop a system which would meet the desired objectives.

As the project developed, it became necessary to separate the projectile into subsystems in order to provide in depth analysis on different schemes that could meet the design objectives. The author specifically contributed to the design of the communications subsystem, so this thesis will concentrate heavily on that subsystem, though others will also be discussed.

The project is a two year project while this thesis only covers the first year of development. The status of the design, as well as the prospects for the future are discussed in detail.